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Developing and testing a model of wind damage risk for forest plantations in South-West Europe

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Declaration

I, Tommaso Locatelli, confirm that the work submitted is my own, except where work which has formed part of jointly-authored publications has been included. The thesis contains three core chapters in press or submitted for publication in peer-reviewed journals. Details of each proposed publication, including an outline of the candidate's and co-authors' contributions, are given below.

I confirm that appropriate credit has been given within the thesis where reference has been made to the work of others.

No part of this work has been submitted for any other degree or professional qualification.

I, as lead author, performed the experiments, model simulations, data and statistical analysis, and writing of the papers. Co-authors provided support and guidance on the scope and design of the project, the fieldwork performed, and contributed to the editing of the manuscripts.

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Lay summary

Wind disturbance to forests is a recognised driver of ecological succession, as patches are created within the canopy, favouring light penetration to the understorey, creating favourable conditions for the regeneration of the forest, and promoting biodiversity. While these natural processes can provide long-term benefits to natural forests, they also represent a major challenge for managed forests and plantations where the focus is on productivity of the stand, be it in the form of timber, pulp for paper production, or for biomass. Indeed, wind is the major abiotic hazard to forests worldwide, especially in areas characterised by intensive management of plantations, such as Europe. Due to the combination of locally adopted species, intensive silvicultural management practices, and environmental and climatic conditions, certain areas have been more susceptible to wind damage. One of such areas is the Aquitaine region in South Western France, where storms Martin in 1999 and storm Klaus in 2009 severely affected the forestry sector.

A first approach to the study of the risk of wind damage to forests consists of statistical methods, where data are gathered after a damaging event: from tree characteristics, to soil types and conditions, to features of the landscape that can affect local wind speeds. While these studies are invaluable in that they can highlight the main drivers of wind damage risk, their predictive power is limited to the specific conditions from which they were built. An alternative, more solid approach is provided by semi-mechanistic mathematical models, such as ForestGALES, which approximate the dynamics of wind damage at the stand and tree levels. These models are not entirely devoid of empiricism, as they rely on tree-pulling fieldwork to model a tree's resistance to overturning. A common issue with complex models is the sensitivity of their predictions to variations in the input variables.

Fieldwork was carried out on *Eucalyptus globulus* (Labill.) trees in the Asturias region in the North of Spain to parameterise ForestGALES for this economically globally important plantation species. This allowed to compare the vulnerability of this species with that of *Pinus pinaster* (Ait.), another important plantation species with similar intended uses that is extensively adopted in Aquitaine. The results show that the fast growth rates of *E. globulus* are responsible for the higher vulnerability of this species, and that the presence of upwind gaps exacerbates the risk of damage. However, fast growth rates allow for good returns from early thinnings, and for the possibility of multiple rotations within a short time span. As a consequence, the cumulative risk within a single rotation is largely reduced, making *E.*

globulus a suitable alternative to *P. pinaster* from the viewpoint of vulnerability to wind damage. A sensitivity analysis of ForestGALES has shown that the model identifies correctly the main drivers of risk: tree height, stocking density, diameter at breast height, and presence of an upwind gap. However, the contributions of different soil types and rooting depths (the empirical component of the model) are negligible. These results suggest that the main architecture of the model is solid, and that the model can be used for large-scale applications, but that further research should focus on improving the empirical component of ForestGALES.

Abstract

Wind is the main abiotic cause of disturbance to forests in large parts of the world, particularly at temperate and boreal latitudes. In the past few decades the consequences of large wind-induced losses have been experienced at various levels, from small forest owners to large-scale, whole-society level. This is particularly relevant for areas, such as Europe, where forests are intensively managed, and the assets exposed to wind hazard are substantial. To better manage forests and commercial tree plantations to reduce the risk of wind damage, process-based, semi-mechanistic mathematical models such as ForestGALES are used. This model has been parameterised and evaluated for numerous conifer species, which constitute the major plantation types in temperate and boreal biomes. However, the geographical extent and economic importance of fast-growing broadleaved species, such as those of the *Eucalyptus* genus, and the lack of detailed historical data on wind damage to these species, require that tools for the estimation of the risk of wind damage to these species are developed and evaluated. This is particularly relevant in light of the projected increases of surface temperature due to climate change, and of the frequency and severity of extreme windstorms, that are expected as a consequence of climate change.

Fieldwork was conducted in a semi-natural *Eucalyptus globulus* (Labill.) forest in the Asturias region in Northern Spain to acquire data for the parameterisation of ForestGALES for *E. globulus*, using a tree-pulling experiment. The behaviour of the parameterisation was investigated for different stocking densities to evaluate whether the effects of tree height, stocking density, and presence of a fresh upwind gap are consistent with the literature. This parameterisation was then used to compare the vulnerability to wind damage between *E. globulus* and *Pinus pinaster* (Ait.), the predominant plantation species in the Aquitaine region of SW France where extensive damage was experienced from storms Martin (1999) and Klaus (2009). The effects of rooting depth (2x), growth rate (2x), presence/absence of a recently created windward gap, and of the predominant wind climate in Aquitaine were investigated in this comparison. In order to aid forest managers with optimal resource allocation for practical applications of ForestGALES, and to provide forest modellers with invaluable insights for the development of robust wind damage risk models, ForestGALES was subjected to a sensitivity analysis. A generalisation of the variance-based method of Sobol' for the case of correlated variables was used to investigate the sensitivity of the

outputs of ForestGALES (the critical wind speeds for stem breakage and uprooting, and the associated probabilities of damage) to variation in its input variables.

Almost all the *E. globulus* trees pulled in Asturias failed by overturning rather than breakage, which allowed for good confidence in the calculations of the overturning moments required for the empirical component of ForestGALES. Resistance to overturning was not significantly influenced by the presence of a tap-root. Modelling the shape of the tree crowns with an ellipsoid provided a good approximation of the geometry of the canopy, but required additional fieldwork as crown width in the four cardinal directions had to be estimated visually prior to the tests. The scarcity of detailed published data on wind damage to *E. globulus* made evaluating the parameterisation particularly challenging. This impediment was obviated by investigating the behaviour of the parameterisation with regards to the well-known effects of tree height, stocking density, and presence of a fresh upwind gap. The simulations showed that the parameterisation behaved as expected, with vulnerability of *E. globulus* stands increasing with tree height, stocking density, and the presence of a gap. High initial planting densities, an early thinning, and a final harvesting before the trees have reached a height of 20 – 25m are recommended to reduce the risk of wind damage to *E. globulus*. The comparison with *P. pinaster* showed that *E. globulus* trees are particularly susceptible to the presence of a recently created windward gap. Therefore, harvesting at neighbouring sites should be minimised, and preferentially performed when the neighbouring stands are still at a young age to take advantage of the fast growth rates of *E. globulus*. These practices would ensure that in case of wind damage any losses are recovered in a short time. These procedures can reduce the cumulative risk through the rotation, while maintaining competitive yields. The ForestGALES simulations have also highlighted that the silvicultural practices currently in place in Aquitaine expose *P. pinaster* trees to high levels of cumulative risk (> 20%).

The sensitivity analysis of ForestGALES has highlighted the strengths of the model and the areas that require substantial improvement. The results of the analysis show that ForestGALES is able to simulate very effectively the dynamics of wind damage to forest stands, as the model architecture reflects the significant influences of tree height, stocking density, dbh, and size of an upwind gap, on the calculations of the critical wind speeds of damage. Similarly, in ForestGALES the wind climate of a site is the main driver of variation of the probabilities of damage, as it is for real forests affected by extreme storms.

Conversely, when the windiness of a site is moderate, ForestGALES accounts for the larger role of tree and stand variables. The sensitivity analysis has shown that ForestGALES is particularly efficient at simulating not only the effect of the size of windward gaps on the vulnerability of a stand, but also at differentiating between recently formed stand edges and edges that have been in place since the establishment of a stand. Therefore, for practical applications of the model, tree height, dbh, stocking density, the size and nature of an upwind gap, and the local wind climate, are the variables that need to be known with a high accuracy in order to maximally reduce the uncertainty of the model predictions. The section of the model that requires further attention and research is the one dedicated to the calculation of the trees' resistance to overturning. The sensitivity analysis has shown that rooting depth and soil type, the model input variables on which the empirical component of ForestGALES that describes the resistance to overturning is based, contribute only marginally to the variation in the outputs. This finding unequivocally identifies that efforts for future research should be aimed at studying the mechanics of root-soil interactions with regards to tree stability. The results of the sensitivity analysis have also shown that the variance-based method used in this research project is equally sensitive to the accurate description of the probability distribution functions of the scrutinised variables, as it is to their correlation structure.

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The University of Edinburgh and the UK Forest Research inspired me from the moment I sat my interview for this project, and never failed to do so throughout the time it required me to complete it. I am extremely grateful to everyone I have met at both institutions for constantly reassuring me that I was in the right place, and for helping me realise that the relevance of my research encompasses equally the natural world and human societies. This last point is of great importance to me, as it satisfies my innate desire to understand the workings of our precious environment, with the aim to contribute to the sustainable and healthy relationship that us humans need to strengthen with our habitat.

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Thank you.

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Table of Acronyms and Symbols

CDF	Cumulative density function
CPD	Cumulative probability of damage
C_{reg}	Overturning moment coefficient, empirically derived from tree-pulling tests
CWS	Critical wind speed(s)
CWS_B	Critical wind speed for breakage
CWS_O	Critical wind speed for overturning
DAMS	Detailed aspect method of scoring, a British measure of the windiness of a site
Dbh	Stem diameter at breast height (1.3m)
FF	Factor fixing, a setting of global sensitivity analysis
FM	Factor mapping, a setting of global sensitivity analysis
FP	Factor prioritisation, a setting of global sensitivity analysis
GSA	Global sensitivity analysis. In this thesis this is used to refer to the variance-based method of Sobol' and its generalisations
MAI	Mean annual increment, the average annual growth that a stand has exhibited to a certain age
MC	Moisture content of wood
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
PDF	Probability density function
$Prob_B$	Probability of breakage
$Prob_O$	Probability of overturning
RD	Rooting depth
SA	Sensitivity analysis
S_i	First-order sensitivity index

SI_{10} ……..	Site index at age 10, the average dominant tee height in a stand at 10 years
Sph ……..	Stems per hectare
ST ……..	Soil type
S^T_i ……..	Total sensitivity index
Vol/Ha……..	Volume of timber per hectare

Chapter 1 Introduction

Causes of damage to forest ecosystems can be broadly divided as environmental, that is, caused by natural hazards, and anthropogenic. The former can be further sub-divided according to the nature of the agents responsible for the damage. Biotic sources of damage include that from herbivory (e.g. deer, as in Fuller and Gill, 2001), insects (e.g. green straw aphid, as in Straw et al., 2000), and diseases induced by pathogenic microorganisms, such as fungal infections (e.g. *Phytophthora lateralis*, as in Gibbs et al., 1999). The main abiotic sources of damage to forest ecosystems are drought, fire and wind (Gardiner and Quine, 2000; Schelhaas et al., 2003). Which of these will be most predominant in any given region depends on a number of environmental factors, such as latitude, topography, elevation, local wind climate and temperature profiles, and annual water balance (Lorz et al., 2010; Schelhaas et al., 2010). Particularly damaging biotic attacks on trees often follow abiotic events, when trees have become more susceptible to damage by insects and pathogens (Hanewinkel et al., 2008). Similarly, the risk of wind damage is higher in forests previously affected by fire (Cannon et al., 2015), pathogens (Eriksson et al., 2008), and insects (Taylor and MacLean, 2009).

As described in the next sections of this Introduction, wind damage to natural and planted forests is a phenomenon that pertains to different geographical and societal scales. This thesis focusses on the study of the risk of wind damage, from the point of view of the mathematical modelling of the mechanical processes involved in wind damage at the tree and stand levels, to the practical applications of such models to aid foresters in the management of commercial stands. For the scope of this thesis, I will focus on damage at tree, stand, and regional levels. More specifically, damage at tree level is defined here as uprooting (or overturning) or stem breakage under wind loading. With regards to the concept of risk (defined for the purpose of this thesis in Section 1.3), the work presented in this thesis is related to the evaluation and management of the vulnerability of forest stands exposed to wind hazard, and the associated risk of damage. In line with good modelling practice, uncertainty and sensitivity analyses of the mathematical model adopted for this study are presented to unambiguously identify and rank the model input variables that drive most of the variation in the outputs.

In this chapter, wind damage to forest ecosystems at different scales is briefly discussed (Section 1.1). Section 1.2 reports on the economic, societal, and ecological impacts of large-

scale wind damage to forests. The definition of risk of wind damage to forests used in this thesis, and the management strategies to mitigate such risk, are described in Section 1.3. Section 1.4 introduces past and current approaches to the study of the risk of wind damage. Section 1.5 constitutes an introduction to the characteristics and geographical distribution of three commercially important tree species that have suffered extensive wind damage: Sitka spruce (*Picea sitchensis* (Bong.) Carr.)), maritime pine (*Pinus pinaster* Ait.), and *Eucalyptus globulus* (Labill.). The latter species, the commercial importance of which for plantations worldwide is increasing, has not been previously modelled for the risk of wind damage. In Section 1.6, the importance of subjecting mathematical models to a sensitivity analysis and the applications of such techniques are discussed, together with an introduction to the relevant techniques used in this thesis. Lastly, Section 1.7 provides an overview of this thesis and its objectives.

1.1 Wind damage at different scales

Wind is the main agent of disturbance to forests in temperate and boreal biomes (Schelhaas et al., 2010). For instance, wind was responsible for 53% of timber damaged in Europe by natural hazards (biotic and abiotic) in the period 1950 – 2000 (Schelhaas et al., 2003). Wind damage to trees and forests is experienced at different scales, from leaves to the regional scale. This study is primarily concerned with damage at the levels of the individual tree, and at stand and regional levels. In order to provide some context for the following sections, examples of damage at leaf and canopy scales are briefly discussed below. Figure 1.1 pictorially summarises the scales of wind damage to trees and forests.

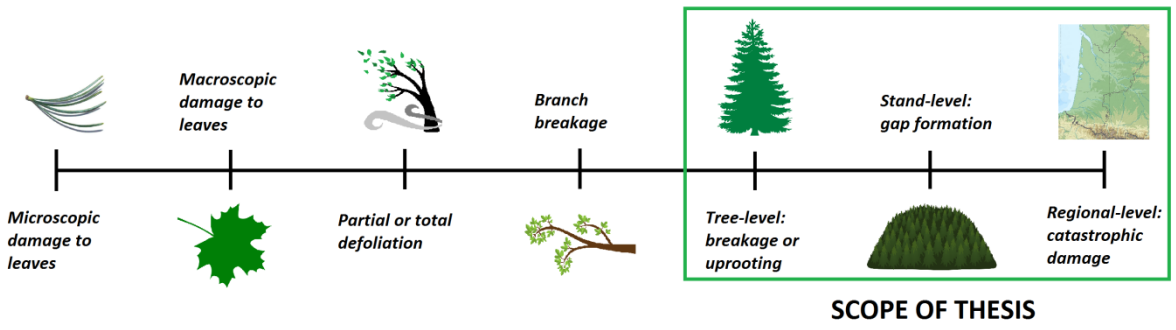


Figure 1.1 - Increasing levels of wind damage, from leaves to entire geographical regions.

1.1.1 Wind damage at the leaf scale

At the smallest scale, damage to leaves of broadleaved trees and conifer needles can be microscopic or macroscopic (leftmost side of Figure 1.1). Hadley and Smith (1989) have shown the effect of wind speeds of about 12 m s^{-1} on the reduction of leaf surface wax over the winter period in specimens of *Picea engelmannii* (Parry ex Engelm.), *Pinus contorta* (Douglas), and *Abies lasiocarpa* (Hook.) Nutt., resulting in leaf desiccation. Leaf surface waxes are involved in the control of leaf transpiration, which is especially important in periods of drought. In boreal ecosystems, trees experience water scarcity, typical of dry summer months, also in winter, when water is not available to the plant because it is primarily in the form of ice and snow, and windstorms are most severe. Wind-induced loss of waxes is not restricted to conifer needles, but is also experienced by leaves of deciduous trees such as *Acer pseudoplatanus* (L.), as shown by Wilson (1984). Because of the lower rigidity of the leaves of broadleaved trees, microscopic damage can happen at much lower wind speeds. Wilson (1984) applied wind speeds of 3.5 m s^{-1} in her wind-tunnel experiments and noted that the principal damage mechanism to the leaves was the abrasive contact between wind-exposed leaves. Structural components of the leaves, responsible for fluid transport, were also damaged. Wilson (1980) observed macroscopic wind damage in the form of tearing and shredding of young leaves of *Acer pseudoplatanus* (L.), showing a linear correlation with increasing wind speeds (maximum of 6.3 m s^{-1}) and length of exposure in the wind-tunnel (up to 8 days). Vogel (2009) confirmed that these types of wind damage are most common in newly budded leaves. Wind damage at the leaf scale to forest stands in proximity of a coastline can also occur as a consequence of marine aerosol deposition. This is particularly concerning for species with a low salt tolerance and mostly affects the tallest trees in a stand (Edwards and Holmes, 1968; Gustafsson, 1997). At high concentrations, sodium chloride is toxic to the foliage of salt-intolerant trees, and it is of particular concern during dry strong winds, i.e. storms not accompanied by rainfall which can precipitate marine aerosols before they are deposited on trees (Aamlid and Horntvedt, 2002; Bussotti et al., 1995). Similarly, wind-driven particles (ice or soil) are believed to be responsible for bark-stripping induced cambial mortality in tees growing under harsh environmental conditions, such as *Pinus aristata* (Engelm.) and *Thuja occidentalis* (L.) (Boyce and Lubbers, 2011; Matthes et al., 2002; Schauer et al., 2001).

1.1.2 Wind damage at the canopy scale: foliage and branches losses

As shown in Figure 1.1, tree canopy is the next level at which wind damage can occur. Partial and total defoliation is more common in deciduous species and is caused by failure of the leaf petiole during strong winds (Metcalfe et al., 2008). In their analysis of hurricane damage to native and exotic tree species in the south-western United States, Duryea et al. (2007a, 2007b) have shown distinct differences between tree species in their tendency to shed leaves during hurricane exposure (minimum wind speed: 38 m s^{-1}). The authors also noted that for some species, mostly the native ones in their study, extensive defoliation was correlated with better tree survival assessed shortly after the hurricane (<7 days), suggesting a reduction in canopy resistance, or drag, to wind loading as the mechanism responsible for higher survival rates. However, large foliage losses in the summer months can have a large impact on future tree survival as the requirements of the tree with regards to photosynthesis and gas exchange cannot be satisfied in the total absence of leaves. Duryea et al. (2007a) also reported on branch losses caused by hurricanes and found a strong positive correlation with stem diameter and proportion of branch loss, confirming the findings of Glitzenstein and Harcombe (1988) in their study of the effects of a tornado in Texas in 1983. Indirect damage following branch breakage to large trees can severely impact understory trees (Frangi and Lugo, 1991).

1.1.3 Wind damage to whole trees and forest stands

The mechanical forces acting on a tree during a windstorm are exerted by the wind itself and by gravity. Momentum transfer from the wind to a tree is applied by way of canopy resistance to the wind (Mayhead et al., 1975) and produces bending stresses in the stem (Milne, 1995) and in the roots (Coutts, 1986). The force of the wind (F_{Wind}, in Newtons) acting at any height *z* up a tree is calculated as follows (Peltola, 2006):

$$\boldsymbol{F_{Wind}} = \frac{1}{2} \cdot \boldsymbol{C_d} \cdot \boldsymbol{\rho} \cdot \boldsymbol{u(z)^2} \cdot \boldsymbol{A(z)} \quad \textbf{(1.1)}$$

Where *Cd* is the drag coefficient of the tree canopy (dimensionless), ρ is the air density (kg m^{-3}), *u(z)* is the mean wind speed (m s^{-1}) at height *z*, and *A(z)* is the streamlined projected area (m^2) of the canopy and stem of the tree at height *z*. As a tree is swayed from its vertical axis under the action of the wind, an additional force (F_{Tree}, in Newtons) is provided by the

gravitational force acting on the masses of the stem, canopy, and snow, when applicable (Peltola, 2006). This gravitational force can similarly be calculated at any height *z*:

$$\boldsymbol{F_{Tree}(z) = M(z) \cdot g} \quad \textbf{(1.2)}$$

Where *M(z)* is the mass (kg) of the tree components, and snow when applicable, and *g* is the gravitational constant (m s^{-2}). Using equations (1) and (2) it is possible to calculate the total bending moment resulting from wind and gravitational forces, at any point along the stem:

$$\boldsymbol{BM_{max}(z) = F_{Wind} \cdot z + F_{Tree} \cdot x(z)} \quad \textbf{(1.3)}$$

Where *z* is the height along the tree (m) and *x(z)* is the horizontal displacement (m) of the tree under the wind loading. The horizontal displacement is assumed proportional and inversely proportional, respectively, to the force of the wind and the stiffness of the stem (Peltola and Kellomaki, 1993). The stiffness of the stem is defined as the product of the Modulus of Elasticity of stem wood by the second moment of area of the cross section of the stem (i.e. EI), calculated from the stem diameter (Wood, 1995). The stem and the root-soil plate provide resistance to breakage and overturning, respectively. These resistive moments are the result of stem stiffness, wood strength, weight of the root-soil plate, structural strength of the roots, and the soil shear strength. Figure 1.2 provides a diagrammatical representation of these forces.

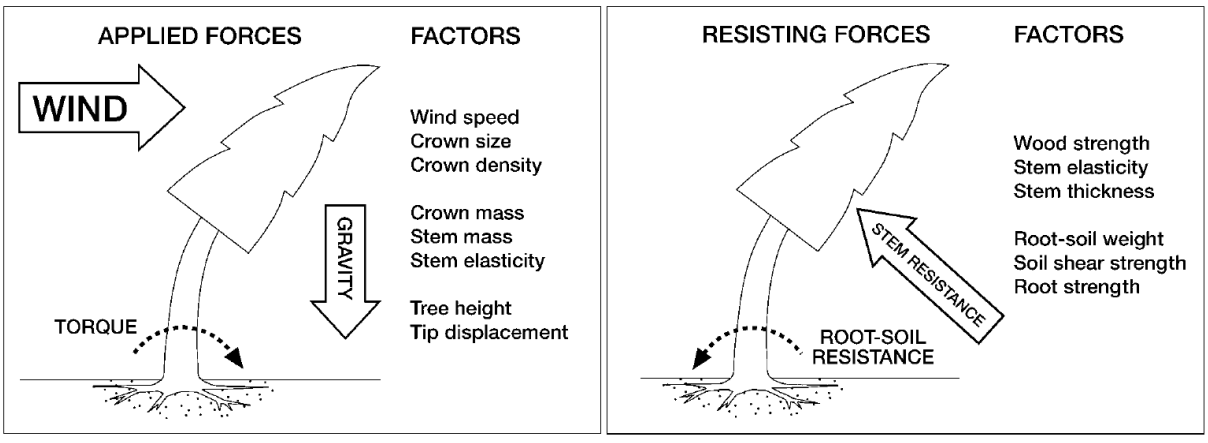


Figure 1.2 - Applied and resistive forces on a tree subject to strong winds (from Peltola, 2006)

Tree anchorage can be impaired when trees are shallow-rooted, as in poorly drained soils which are not favourable to the development of sinker roots or taproots, which can provide the tree with additional anchorage (Peltola, 2006). This often happens when a hardpan layer

is present in the soil at shallow depths, raising the water table (Danjon, 2005). Under such circumstances, and in the absence of further constraints, trees devote their resources on the radial and lateral development of roots to improve anchorage (Nicoll et al., 2006; Ray and Nicoll, 1998). Coutts (1986) reports that when mechanically uprooting shallow-rooted Sitka spruce trees (*Picea sitchensis* (Bong) Carr.) under static forces, the root system component that provided most of the anchorage at maximum load was the windward roots. At high latitudes, ground frost can improve tree stability during winter months (Peltola et al., 1999). Tree resistance to breakage is based on the assumption that stress from wind loading in the outer fibres of the stem is constant along the height of the stem between the base of the canopy and the base of the tree (Morgan and Cannell, 1994). Following this, calculation of the stress can be performed at just one height (e.g. breast height, 1.3m). When the calculated stress exceeds the Modulus of Rupture of green wood, it is predicted that the tree stem will break (Peltola, 2006). It is known that the presence of wood knots can decrease stem strength (e.g. Lavers, 1969).

The type and severity of wind-induced structural damage to trees and forests depend on numerous factors, from tree, stand and site characteristics to the regional climate (Hanewinkel et al., 2013). The main variables influencing resistance to wind damage are summarised in Table 1.1.

Table 1.1 - Tree, stand, site, and regional climatic factors affecting tree stability

Factors influencing resistance to wind damage		**Comments**	**References**
Tree – level			
	Tree species	Intra-specific differences in wood strength, canopy characteristics, root system, growth rates	Cameron and Dunham (1999) Dunham and Cameron (2000) Hale et al. (2015) Hanewinkel et al. (2013) Mason and Valinger (2013) Peltola et al. (1999)
	Tree height	Higher wind risk generally associated with taller trees due to increasing lever arm	
	Stem diameter	Dbh (diameter at breast height) recognised as main predictor of tree response to wind loading: the larger the dbh, the greater is the resistance to wind loading.	
	Tree taper	High taper associated with higher stability	
	Tree age	Very young trees (toppling), juvenile, and old trees estimated at higher risk	

	Crown shape and streamlining	Important factors governing "sail" area exposed to wind drag	
	Wood knots	Known to reduce stem elasticity	
	Root architecture	Heavily branched roots provide better anchorage; large tap-roots provide stability	
	Tree position within a stand	Trees at stand edge and within ~5 tree heights usually at higher risk when edges are newly formed	
Stand - level			
	Spatial distribution of trees	Regular, close spacing is believed to limit wind penetration in stand	Dunham and Cameron (2000) Mason and Valinger (2013) Nicoll et al. (2009) Peltola (2006) Wood et al. (2008)
	Age distribution of trees	Heterogeneous age distribution provides more resilience to damage	
	Newly formed gaps	Newly formed patches (i.e. from thinning or harvesting) increase wind penetration within stand, increasing risk	
	Stand orientation in regards to prevailing winds	Stands oriented at an angle towards prevailing wind directions believed to be at lower risk	
Site - level			
	Soil type and quality	Soil acidity correlated with storm damage. Important, complex interactions between tree species and soil type in terms of resistance to wind loading	Albrecht et al. (2012) Gardiner et al. (2008) Jactel et al. (2009) Mayer et al. (2005) Nicoll et al. (2006) Quine et al. (1995)
	Soil drainage ability	Poorly drained soils can become waterlogged and reduce tree anchorage	
	Topography	Windward upward mild slopes correlated with stronger gusts	
	Distance between stands	Relative position of neighbouring stands can affect wind direction and velocity	
Regional Climate			
	Temperature	Influences choice of tree species and rate of tree growth. Also affects soil moisture.	Beese (2001) Blennow et al. (2010) Kilpelainen et al. (2010) Nicoll et al. (2006) Peltola (2006) Ruel (1995)
	Soil frosts	In areas with winter occurrence of soil frosts, reduction or absence of ground frosts during winter (period of strong winds) reduce tree stability	
	Rainfall	Intense periods of heavy rainfall increase soil runoff and may cause waterlogging in poorly drained soils, limiting tree anchorage	

	Snow and ice loads	Additional load of ice or frozen snow on trees reduces the wind speed able to cause wind damage, therefore increasing the risk of damage	

1.2 Large scale storm damage in managed and natural forests

Boreal regions, located between latitude 45° and 65°N, are home to the forest ecosystems most affected by wind damage worldwide. The strong winds responsible for the large European timber losses are the result of extratropical cyclones that undergo a phase of intensification in the North Atlantic Ocean before moving eastwards towards mainland Europe (Liberato et al., 2010). From European meteorological records, an increase in frequency and severity of extreme winds in the last 25 years cannot be inferred (Blennow and Olofsson, 2008). However, simulations of high-resolution global climate models suggest that a surface temperature increase of the Atlantic Ocean at tropical latitudes might increase the frequency and intensity of damaging storms (Haarsma et al., 2013). Since the Vivien/Wiebke storms in 1990 Europe has been subject with unusual frequency to storms characterised by extreme wind speeds. The European records of storm-damaged timber show a marked increase during the last three decades, which is attributable to the extensive adoption of intensive modern silvicultural practices and larger standing timber volumes exposed to environmental hazards (Jactel et al., 2009; Schelhaas et al., 2010). Indeed, despite accounting for only 5% of the world's forested area (FAO, 2010), European forests are some of the most intensively managed forests in the world (Jactel et al., 2009), with an annual growing stock of 156 m^3 ha^{-1}, second only to South America (FAO, 2010).

1.2.1 Economic impacts of wind damage to forests

Intensive forest management practices, in addition to the geographical concentration of planted forests in Central Europe, have resulted in this area being particularly affected by wind damage. The European countries most affected in terms of timber and economical losses are Switzerland, Austria, and France (Caurla et al., 2015; Costa et al., 2009; Cucchi and Bert, 2003), Germany (Hanewinkel et al., 2011; Schelhaas et al., 2010; Teich and Bebi, 2009), and the Scandinavian region (Blennow et al., 2010; Kilpelainen et al., 2010; Nilsson et al.,

2004). Great Britain has been affected by five major storms between the 1950s and 1990s, with significant timber losses estimated at around 9.6 Mm^3 (Dannatt et al., 1989; Mackenzie and Martin, 1971; Quine, 1991). In comparison, the Vivien/Wiebke storms in February/March 1990 caused timber losses of more than 100 Mm^3 in mainland Europe, mostly concentrated in Germany, Austria, and Switzerland (Schindler et al., 2012; Usbeck et al., 2010; Wohlgemuth et al., 2002). The end of the 20th century has seen the most damaging storms recorded in Europe to date, with the Lothar/Martin storms in 1999 which caused losses of more than 240 Mm^3 of timber (Gardiner et al., 2010; Schuck and Schelhaas, 2013). Forests and plantations in France were particularly affected by the Martin storm of 1999, especially in the south-western Aquitaine region. French timber losses were estimated at 176 Mm^3 (equivalent to ~3.5 harvesting years; Schuck and Schelhaas, 2013), of which 26.1 Mm^3 mostly occurred in Maritime pine (*Pinus pinaster* Ait.) plantations (Cucchi et al., 2004). Ten years later, in January 2009, storm Klaus hit France and again in Aquitaine, where 37.1 Mm^3 of the total 42 Mm^3 of windfall were lost (Bavard et al., 2013), resulting in an economic cost estimated between 1.34 and 1.77 billion Euros in Maritime pine plantations alone (Lecocq et al., 2009). This figure also comprises losses in market value, future forest products' value, reforestation costs, and indirect damage to the affected stands (Costa et al., 2009). The Gudrun storm in January 2005 led to the loss of 75 Mm^3 of timber in Sweden, a loss almost equivalent to the nation's annual average harvest (Gardiner et al., 2010). In January 2007, storms Kyrill and Per passed over Central Europe and Central Scandinavia, causing timber losses of 54 Mm^3 and 12 Mm^3, respectively (Gardiner et al., 2010; Schuck and Schelhaas, 2013).

Other parts of the world have been severely affected by windstorms. In the northern hemisphere, areas most notably affected are the USA and the Caribbean (Everham and Brokaw, 1996; Peterson and Pickett, 1991; Uriarte and Papaik, 2007), and Japan (Kamimura and Shiraishi, 2007). In the southern hemisphere, studies on wind damage have been principally carried out in New Zealand (Somerville, 1995), where damage to managed conifer forests in the 4 decades before 1990 has been reported on an area of around 50,000 ha (Moore and Quine, 2000). In Australia, studies of the effects of wind on forests are scarce and mainly focussed on Eucalypts plantations, for which data on wind-throw is quite scarce (Gerrand et al., 1997; Williams and Douglas, 1995; Wood et al., 2008). Even scarcer are studies of wind damage in South America, with a few notable exceptions. In one of the first published papers on wind damage in the Amazon forest, Nelson et al. (1994) adopted Landsat imagery to investigate the occurrence of fan-shaped blowdowns. The authors reported a

wide range of areas affected by windthrow, from small patches of 5 ha to 3,400 ha. Although information on the windstorms which affected the areas was not available, the authors ascribed the damage to wind because of the absence of roads and inhabited centres nearby the windblown areas. The other few studies on wind damage in South America focus on a single cross-basin squall event in 2005, which moved from south-western Brazil to the north-east. About 30% of the forested area in the region, estimated to correspond to a loss of mean annual biomass accumulation of about 23%, was lost because of this event (Marra et al., 2014; Negron-Juarez et al., 2010). Plowes (2002) reports wind damage to the Bunga natural forest in Zimbabwe in 2000, caused by cyclone Eline, which was characterised by gust speeds exceeding 42 m s^{-1} and a particularly large span, having travelled westwards for more than 80^{o} of longitude. About 200 large trees were affected totalling an area of less than 2 ha. The main mode of tree failure was overturning, which the author ascribed to the waterlogged soils caused by the abundant rainfall prior to the storm.

In managed forests and commercial plantations, the economic impacts of windstorms are complex and considerable, and extend beyond the direct loss of timber. The industry sectors primarily affected by a damaging windstorm are the primary wood processors of sawnwood, wood panels, and pulp (Hanewinkel and Peyron, 2013). The large amount of salvaged wood saturates the markets of timber and forest products, and the quality of the extracted timber is lower. As a consequence, the unit prices of timber and related products suffer dramatic reductions (Hanewinkel and Peyron, 2013; Schwarzbauer and Rauch, 2013). For instance, it is estimated that France alone has lost $6 billion in timber revenues following the Lothar and Martin storms (Schuck and Schelhaas, 2013). The costs associated with unscheduled silvicultural practices add to the loss of timber. These include logging of damaged trees, clear-felling of adjacent stands to reduce future damage, and ground clearing for fire prevention. Premature harvesting of unaffected stands typically results in revenue loss, since these stands have not yet completed their optimal rotation (Hanewinkel and Peyron, 2013). Secondary damages to forests following windstorms can increase costs if salvaging operations are not timely, as they can result in further timber losses (e.g. from disease, insect outbreaks and fire). Furthermore, ad-hoc planning is required for salvage operations and to mitigate future losses (Hanewinkel et al., 2013; Orazio, 2013; Peltola, 2006). While the size of the forest insurance sector is still small in comparison to the traditional insurance sectors of pensions and life insurance, the last 10 years have seen a steady increase in the number of forestry and plantations projects seeking insurance from natural damages. The perceived

unpredictability of catastrophic wind events has restrained insurers from providing their clients with coverage against wind-induced losses. Forest owners have similarly avoided seeking such coverage in areas not historically affected by strong winds, which in certain cases, such as in Uruguay in 2009, caused massive losses (Phil Cottle, *pers. comm.*). In most European countries insurance against wind damage is available and partially state-subsidised, although losses due to the reduced price of timber are typically not covered. The insurance sector becomes particularly active after a major windstorm and due to the potential for very large claims it can suffer large losses (Gardiner and Welten, 2013; Hanewinkel and Peyron, 2013).

1.2.2 Societal consequences of wind damage to forests

Catastrophic wind damage to forests also has societal and ecological impacts. Loss of human life can happen as a direct and indirect consequence of wind damage to forests. The storms of 1999 caused the death of 140 people (Gardiner et al., 2010). An increase in accidents, also fatal, to people working in salvage operations shortly after a storm, is well-documented (Gardiner et al., 2010; Ranhoff et al., 1992). On a broad societal level, damage to infrastructures can be extensive. Falling trees and branches often result in blockages of roads and railways which can be affected for days, sometimes weeks. Similarly, interruptions to power lines and non-mobile telecommunication services can be experienced for up to two months after a storm (Gardiner et al., 2010). The people most vulnerable to wind damage to infrastructures are those living in remote areas, which can remain isolated until transport routes are cleared. This can be a particular problem when medical assistance cannot be provided to these communities. Because wind storms in boreal forests are most common in winter, loss of electricity when temperatures fall below 0^{o}C means that alternative methods to provide heating must be adopted. The effect on infrastructures of the damage of the Gudrun storm on Northern European forests deprived 1.4 million people in Lithuania of electricity for a week, while Latvians were without electricity for 23 days. In rural communities, this is likely to promote the use of gas and wood stoves, which can increase the risk of fires (Blennow and Persson, 2013). On a smaller scale, forest owners who managed their forests for long periods, sometimes for generations, might see their forests destroyed by a storm within just a few hours. In addition to the loss of revenue, it is not uncommon that forest owners suffer considerable emotional distress, especially when the relationship with

their forests has familial connotations (Gardiner et al., 2010). In extreme cases, an increase in the rate of suicides has been reported (Blennow and Persson, 2013). Besides forest owners, other members of the public can be affected by wind damage to forests, both emotionally and materially. The aesthetic value of an affected forest is reduced, and recreational activities in forests are often perceived as dangerous after severe wind damage. Wind damage can also negatively affect the tourism sector (Gardiner et al., 2010).

1.2.3 Effect of wind damage on forest ecosystems

In unmanaged forests, infrequent natural disturbances are important drivers of changes in forest ecology, structure, and species composition (Collins et al., 1985). The main effects of windthrow are: increased light availability due to gaps in the canopy; sudden input of nutrients to the forest floor; additional substrate for germination in the form of fallen logs and branches; and the development of pit/mound topography on the forest floor following uprooting. The latter creates favourable conditions for newly established seedlings and saplings, unless they are suppressed by soil slides and pit flooding (Ulanova, 2000). Uprooting can also expose buried seed banks, favours germination, and can promote species diversity (Putz et al., 1983). Broadly speaking, the increased heterogeneity of environmental conditions after a storm translates into potential for more heterogeneous species composition. It is widely accepted that forest composition in tropical areas prone to hurricane disturbance does not resemble a steady-state ecosystem, but rather a heterogeneous continuum of species at various successional stages (Attiwill, 1994). The magnitude of the effects of wind disturbances on forest ecology varies with the scale of the disturbance. Small-scale wind damage (i.e. single trees) favours micro-successional changes to the forest floor in the immediate proximity of the damaged tree, especially in the case of uprooted trees. In fact, as the mineral and humus horizons of the soil are exposed, new micro-habitats are formed for fungi, lichens, mosses, and insects (Jonsson and Esseen, 1990). Medium-scale damage in the form of patchy distribution of windthrow is believed to promote gap-phase dynamics. When the windblown area is small (i.e. less than one tree-height in diameter), the trees at the periphery of the newly formed gaps can quickly fill the canopy gap, especially in the case of broadleaf species (Leemans, 1991). When the affected area is larger, the whole habitat undergoes successional changes, as light becomes more available (Ulanova, 2000). The first individuals to benefit from this are small saplings of the

same species as those that suffered wind damage. These are then followed by secondary, shade-intolerant species (Leemans, 1991). In boreal forests, within 100 years of the disturbance the mature stages of succession are restored in the re-grown vegetation. Large-scale catastrophic damage at the landscape level often destroys the understorey and results in major changes in light availability and soil moisture. At this scale, saplings of the parent, damaged species are partially suppressed, and secondary succession pathways are promoted, resulting in species composition typical of early successional stages (i.e. a mosaic of shade-tolerant and intolerant species) (Leemans, 1991). However, disruption of ecosystem dynamics that provide forest resistance and resilience to future natural disturbances is a major concern after damaging storms (Seidl et al., 2008). The main threats to wind-damaged forests are: sudden exposure of surviving trees to sunlight, resulting in sun scald damage, which has been correlated with sap rot (Bragg et al., 2003); fire and biotic disturbances, to which wind-affected stands are known to become more prone (Hanewinkel et al., 2008; Stadelmann et al., 2013); and wind-induced soil erosion, a consequence of extremely severe wind storms and subsequent unscheduled clear-fellings (Edeso et al., 1999; Lal, 2003).

Soil conditions are drastically modified in the event of large-scale wind damage. Temperature, soil moisture, concentrations of soil nutrients and ions, and soil biota are severely perturbed, especially in the case of widespread tree uprooting. The severity of soil damage is such that, even in the case of shallow uprooting, pre-storm soil conditions are restored within a time scale of 100 – 200 years. When uprooting is deep, pre-disturbance conditions might not be restored even after 300 years (Ulanova, 2000). This is of special concern in regards to the carbon balance of the affected forest, since soils store the largest amount of forest carbon and are one of the largest carbon pools in the world (IPCC, 2014). At a global level, the amount of carbon stored in soils is just slightly larger than that stored in tree biomass. However, wide regional differences exist. In Africa, soil carbon represents less than ⅓ of the total carbon stored in forests, while in Asia, Oceania, and the entire American continent, soil carbon is almost half of the total. In Europe, soils hold more than half of the total forest carbon pool (FAO, 2010). In windblown stands, when the organic horizons of the soil are exposed following tree uprooting, soil carbon is rapidly oxidised and released to the atmosphere as CO_2. In addition to this, fallen logs and branches, and decaying trees and roots, are substrate for saprophytic microorganisms that metabolise cellulose, and lignin over longer time periods, and contribute to the release of forest carbon to the atmosphere. The rates of decay are related to moisture and temperature and follow a

latitudinal gradient, being highest in the tropics (e.g. Chambers et al., 2000; Yatskov et al., 2003). As the forest regrows, it transitions from a carbon source to a carbon sink as trees photosynthetically fix CO_2 into their tissues. In the case of a windblown forest, loss of nutrients from trees and soils occurs as a direct consequence of damage. These losses can be exacerbated by salvage operations that further perturb the soil and can increase leakage of nitrates and heavy metals to aquatic ecosystems. Similarly, storing salvaged logs in the proximity of water courses, or in a lake, can result in leaching of nutrients with subsequent water eutrophication (Gardiner et al., 2010).

1.3 Risk of wind damage to forests: definition and management

In their seminal paper on the quantitative definition of risk, Kaplan and Garrick (1981) defined risk as the combination of probability of a hazardous event and the consequences of that event. With regards to natural hazards, the definition can be made more explicit. Risk can be defined as the combination of the probability of a natural disturbance occurring, the assets' vulnerability to the disturbance, and the assets' exposure to the hazard (Molinari, 2007), as shown diagrammatically in Figure 1.3.

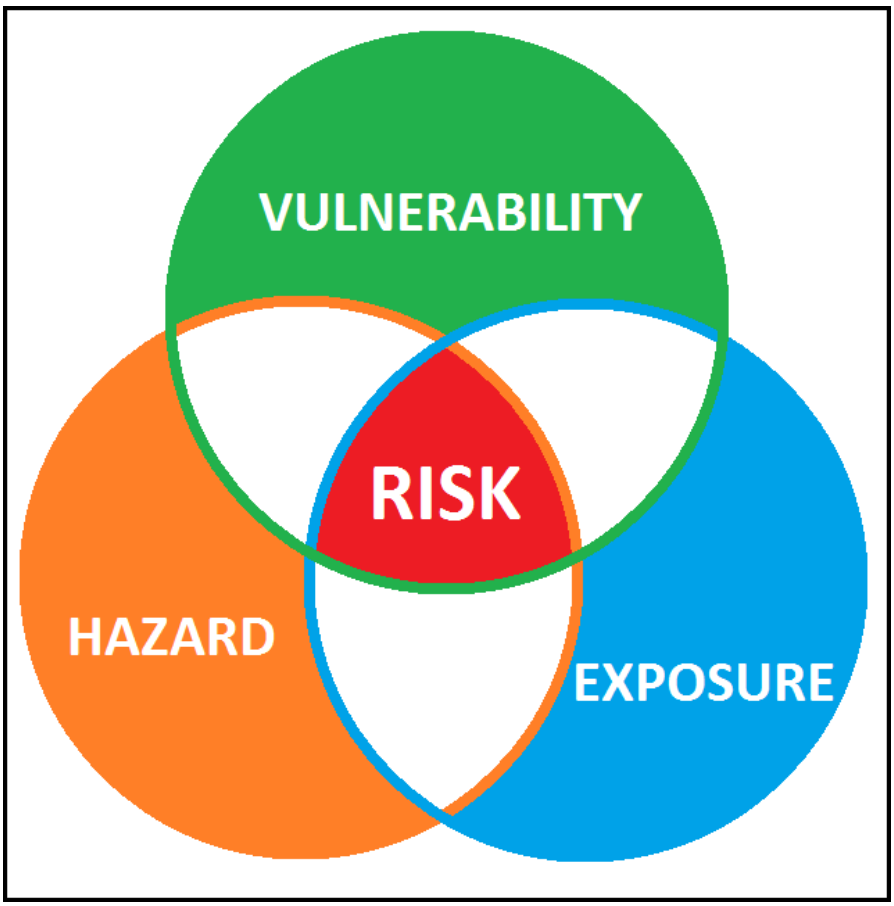


Figure 1.3 - Risk of wind damage to a forest is defined as the combination of the hazard (damaging wind storm), the vulnerability of the forest to wind damage, and the value of the forest assets exposed to the wind storm.

With regards to the risk of wind damage to forests, the probability of a damaging windstorm is expressed as the probability that wind speeds exceed a critical value (Gardiner et al., 2000), that is, the value of wind speeds that cause stem breakage or uprooting. The vulnerability of a forested stand to these hazardous wind speeds depends on a number of factors, summarised in Table 1.1. Some of these factors can be controlled in a managed forest with the appropriate management strategies (Beach et al., 2010; Hanewinkel et al., 2011; Hanewinkel et al., 2013). For instance, species can be chosen on the basis of their (sometimes perceived) resistance to wind damage; thinning of a stand can be performed with intensities and timings that might make the stand less prone to damage; harvesting can be scheduled before the end of the economically optimal rotation length (Miller, 1985); drainage systems can be put in place to prevent soil waterlogging. Other factors are outwith human control, such as air temperature, amount of rainfall, soil type, occurrence of soil frosts, and topography of the planted area. The effect and importance of some of these factors on the

risk of wind damage are discussed in more depth in Chapters 3 to 5. It is important to note that management strategies that reduce vulnerability effectively do so by increasing the critical value of damaging wind speeds, as it is impossible to completely eliminate risk (Kaplan and Garrick, 1981). A reduction in vulnerability feeds back to the probability of exceedance of critical wind speeds, which needs to be re-evaluated. Figure 1.4, taken from Gardiner and Welten (2013), neatly illustrates the link between vulnerability and risk. The authors emphasise that forest management responses to the risk of wind damage are worthwhile only in the case of intermediate risk, whereby when risk is too elevated it is impossible to provide effective responses, while it is economically inconvenient to take any actions to mitigate low levels of risk.

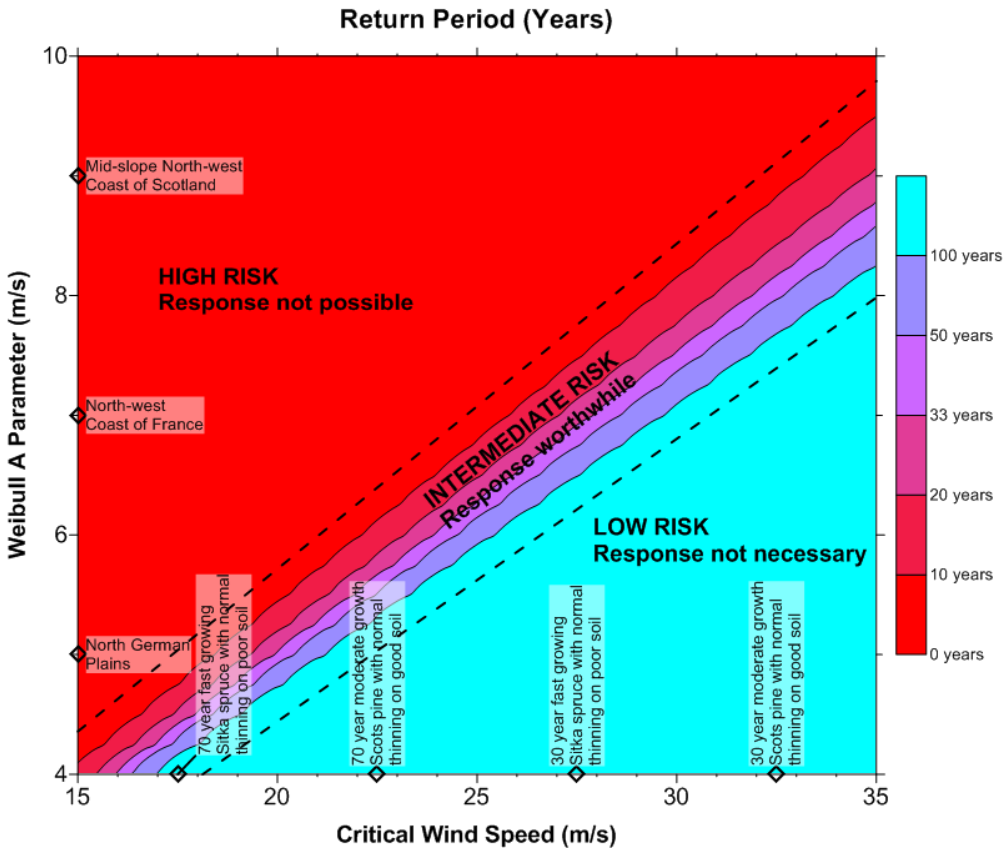


Figure 1.4 - Risk defined as the return period of wind storms with damaging wind speeds. The Weibull A parameter describes the local wind climate, and its values are approximately equal to 113% of the mean wind speed. Examples are given on the horizontal axis of forests of different vulnerability. For instance, a fast-growing 30 years old Sitka spruce with normal thinning on poor soil will start being considered at intermediate risk at a Weibull A parameter above 6 m s^{-1}, as the return period of an associated damaging storm is reduced from 100 years to 50 years. In this example, were the local wind climate to shift to Weibull A values above 8 m s^{-1}, the return period of a storm characterised by this wind climate will be in the order of less than 10 years, corresponding to high risk, when the effect of forest management strategies becomes irrelevant. Image taken from Gardiner and Welten, 2013.

The exposure of forest stands depends on the location of the stand relative to the path of the storm, as well as on the value of the products and services extracted from the forest. The values of these depend on the intended uses of the forest stand, as well as on the specific markets. Forest can be used for timber, pulp, and biomass production, or for provision of ecosystem services such as carbon sequestration, soil protection and formation, biodiversity, and water regulation and supply. It is important to bear in mind that in the case of catastrophic wind damage the market values of forest products and services will decrease, as discussed in section 1.2. An important characteristic of risk is its relativity; for this reason, discussions on risk often adopt the terms “perceived risk” (Kaplan and Garrick, 1981). That is, risk depends on the knowledge of hazard and vulnerability, as well as on the subjective value that stakeholders attach to the exposure (Blennow and Sallnas, 2002). For instance, while storm Gudrun in 2005 impacted the whole of Sweden in terms of tax costs, the country was able to recover relatively rapidly. However, the single forest owners that suffered the largest losses carried the heaviest burden (Blennow and Persson, 2013). Therefore, the perception of the risk of wind damage is very different between, e.g. the average taxpayer and a forest owner.

Having defined risk for the purpose of this study as the interplay between probability, vulnerability, and exposure, I now proceed to describe the approaches to the study of the risk of wind damage to forests.

1.4 Understanding wind damage to forests through models

The scientific approaches and progress in the understanding of the processes of wind damage go hand-in-hand. The two main approaches adopted in the literature are based on statistical and mechanical modelling. Statistical models of wind damage have been adopted at small and large scales (Albrecht et al., 2012). These logistic models aim at identifying the environmental variables and the characteristics of trees and stands that differentiate between the two possible fates of a tree exposed to a windstorm. That is, whether a tree fails either by stem breakage or uprooting, or whether it survives (Hanewinkel et al., 2011). Statistical approaches have been successful at local investigations of the factors involved in wind damage to trees, but are burdened with a number of limitations. The main issue with these approaches is the poor transferability of individual findings for a specific set of species,

in a specific site, subject to a windstorm with specific characteristics (e.g. duration, maximum wind speeds and direction, amount of rainfall), to other damaged forest stands (Lanquaye-Opoku and Mitchell, 2005). As a consequence, statistical models do not lend themselves very well to future prediction of wind risk to stands different from those on which the analysis was conducted. From a broad scientific point of view, the main contribution of statistical approaches is to help build hypotheses of the processes involved in wind damage that can be subsequently tested under controlled experimental conditions (Gardiner et al., 2010). Results from these experiments have contributed, in the last two decades, to the development of mechanistic models of wind damage, discussed in the next section.

1.4.1 Mechanistic models of the study of risk of wind damage to forests

Mechanistic models seek to describe wind damage in terms of causal relationships between the characteristics of a tree, expressed in engineering terms, and the turbulent air flow typical of wind storms (Gardiner et al., 2010). Because they describe mathematically the processes of wind loading on trees, these models are also defined as “process-based”, and have been proposed as a science-driven alternative to statistical models. The two models most frequently adopted in the literature are ForestGALES (Hale et al., 2015) and HWIND (Peltola et al., 1999). A third model, FOREOLE, was developed but never validated (Gardiner et al., 2008). These models however are not entirely devoid of empiricism. In fact, some of the processes involved in the calculation of the profile of the turbulent wind flow over canopies are currently too computationally expensive to model in high detail to apply these models to a broad range of environmental conditions (Dupont et al., 2015). The soil-root interactions responsible for the resistance of trees to overturning also require further study to replace the empirical relationships adopted in the models. These wind-risk models are briefly discussed below. ForestGALES is the model adopted for the simulations in this study, and as such is thoroughly described in Chapter 2.

1.4.1.1 ForestGALES

ForestGALES was developed by researchers at Forest Research in Great Britain to calculate the probability of wind damage to a mean tree in the interior of a stand. The model has been

parameterised for a number of conifer species (see Hale et al., 2015). Chapter 3 provides the first instance of parameterisation for a broadleaf species (*E. globulus*). The model is composed of two main modules: one, called GALES, calculates the critical wind speeds that result in wind damage by uprooting or stem breakage. Another module calculates the probability of exceeding such wind speeds (Gardiner et al., 2008). The critical wind speeds are assumed to follow a logarithmic profile over the canopy in the interior of a stand, and calculated for different species from data on tree height, diameter, spacing within a stand, rooting depth and soil type, and size of a windward gap. The wind loading on an average tree in a stand is assumed to act on the tree at the height of the zero-plane displacement and is a function of the roughness of the canopy surface (Hale et al., 2015). From these parameters the force of the wind is translated into the breaking and overturning moments. ForestGALES makes use of an empirically calculated Gust Factor to model wind turbulence and to translate mean wind loading to maximum wind loading experienced during a storm (Hale et al., 2015). The force necessary for breaking a tree is derived from the Modulus of Rupture of green wood. The resistance of a tree to overturning is empirically derived from linear regressions of stem weight against the overturning moments calculated from field-derived tree-pulling data (Nicoll et al., 2006). The probability of exceeding the calculated critical wind speeds is derived from information on the wind climate of the area of interest (Quine, 2000), and calculated from the return period of storms whose maximum wind speed exceeds the critical wind speeds for breakage and overturning (Gardiner et al., 2000).

1.4.1.2 HWIND

Peltola et al. (1999) developed the HWIND model for the calculation of critical wind speeds of the mean tree at newly created forest edges under Finnish forest conditions. HWIND does not have a module for the calculation of the probability of exceeding the critical wind speeds and hence it does not estimate the risk of damage *sensu stricto*. The calculations of the critical wind speeds are species-specific and require information about tree height, diameter at breast height, stand density, and size of the upwind gap. The force of the wind is calculated at 1m intervals along the height of the stem and crown and summed to give the total force. The additional moment provided by the overhanging weight of the stem and canopy is similarly calculated. Resistance to breakage is a function of the Modulus of Rupture of green wood. The resisting moment to overturning is calculated as a function of root mass and depth

(Gardiner et al., 2000). The mean wind loading is calculated assuming a logarithmic wind profile at the forest edge, and the Gust Factor is used for the conversion from mean to maximum bending moment. In a recent paper by Dupont et al. (2015) HWIND was coupled with the Reynolds-average type airflow model Aquilon. The authors recalculated the Gust Factor from properties of the simulated airflow and suggested more realistic and robust calculations of critical wind speeds.

1.4.1.3 FOREOLE

FOREOLE (Ancelin et al., 2004) was the first attempt to calculate wind loading on individual trees rather than to simulate a stand composed of trees all equal to the mean tree in the stand. This approach allows for the application of a wind damage model to complex stands. The model assumed a constant wind profile within the canopy and used leaf area distributions within a canopy to translate wind speeds to turning moments (Gardiner et al., 2008). Due to the lack of the extensive data required for validation of such a complex modelling approach, FOREOLE has never been fully validated.

1.5 Application of ForestGALES for commercially important tree species

ForestGALES has been favourably received in the scientific community. The model was initially parameterised for a number of conifer species adopted in the United Kingdom for managed forests and plantations using winching data between 1960 and 2000 collected in the British Forest Research (FR) tree-pulling database (Nicoll et al., 2006). Subsequently, several papers have been published reporting tree-pulling tests of other species, as well as to some of the same species from the original dataset but grown in different countries, under different forest management practices, and in different environmental conditions. Table 1.2 summarises this information. Fraser and Gardiner (1967) describe the original approach to tree-pulling experiments. Nicoll et al. (2006) report the modifications applied to the original method in their account of the current approach. For my study I have used their current approach, which I describe in detail in Chapter 2.

In the next paragraphs I introduce the geographical distributions and characteristics of three species representative of as many commercially important tree genera: Sitka spruce (*Picea sitchensis* (Bong.) Carr.), maritime pine (*Pinus pinaster* Ait.), and *Eucalyptus globulus* (Labill.). While ForestGALES has been extensively adopted for stands of coniferous species, including Sitka spruce and maritime pine (e.g. Hale et al., 2004; Cucchi et al., 2005), until now it has not been parameterised for any broadleaved species. Chapter 3 presents the parameterisation and evaluation of ForestGALES for the broadleaf *E. globulus*, accompanied by a preliminary sensitivity analysis of the parameterisation. The results of Chapter 3 are then used in Chapter 4 to compare this species with maritime pine in terms of their vulnerability to wind damage, and the associated cumulative risks of damage. The two species were chosen because they have similar habitat ranges, environmental requirements, and intended uses, and in Europe they are extensively planted in areas (SW France and Northern Iberia) that were exposed to similar wind speeds during storm Klaus (2009). However, while damage to maritime pine plantations was catastrophic (see Section 1.2), the reported damage to *E. globulus* stands was smaller by an order of magnitude, as discussed below. In Chapter 5, ForestGALES is submitted to a thorough sensitivity analysis for the three abovementioned species, with Sitka spruce being used as a benchmark species because of its large dataset (Table 1.2, and Section 1.6, and Chapters 2 and 5, for the importance of the size of a dataset for the sensitivity analysis methods used in this thesis). Section 1.6 provides an introduction to sensitivity analysis, while the technical details of the methods used in Chapters 3 and 5 are discussed in Chapter 2.

Table 1.2 - Species for which ForestGALES has been parameterised to date

Species	Data source	Country where fieldwork was performed	Number of pulled trees	Reference	Name of Model
Sitka spruce (*Picea sitchensis* (Bong.) Carr.)	FR Database[1]	United Kingdom	1155	Nicoll et al., 2006	ForestGALES
Norway spruce (*Picea abies* (L.) H.Karst.)	FR Database[1]	United Kingdom	144	Nicoll et al., 2006	ForestGALES
White spruce (*Picea glauca* (Moench) Voss.)	Bespoke tree-pulling[2]	Canada	80	Achim et al., 2005	ForêtVENT[3]
Black spruce (*Picea mariana* (Mill.) BSP)	Bespoke tree-pulling[2]	Canada	between 40 and 45	Elie and Ruel, 2005	ForêtVENT[3]
Jack pine (*Pinus banksiana* Lamb.)	Bespoke tree-pulling[2]	Canada	between 40 and 45	Elie and Ruel, 2005	ForêtVENT[3]
Scots pine (*Pinus silvestris* L.)	FR Database[1]	United Kingdom	137	Nicoll et al., 2006	ForestGALES
Corsican pine (*Pinus nigra* subsp. *laricio* (Poir.) Maire)	FR Database[1]	United Kingdom	88	Nicoll et al., 2006	ForestGALES
Lodgepole pine (*Pinus contorta* Douglas)	FR Database[1]	United Kingdom	244	Nicoll et al., 2006	ForestGALES
Radiata pine (*Pinus radiata* D.Don)	Bespoke tree-pulling[2]	New Zealand	163	Moore, 2000	ForestGALES
Maritime pine (*Pinus pinaster* Ait.)	Bespoke tree-pulling[2]	France	74	Cucchi et al., 2004; Cucchi et al., 2005	ForestGALES
European larch (*Larix decidua* Mill.)	FR Database[1]	United Kingdom	24	Nicoll et al., 2006	ForestGALES
Japanese larch (*Larix kaempferi* (Lamb.) Carr.)	FR Database[1] / Kamimura (unpublished data)	United Kingdom / Japan	44; 12	Nicoll et al., 2006	ForestGALES
Hybrid larch (*Larix x eurolepis* A.Henry)	FR Database[1]	United Kingdom	n/a[4]	Nicoll et al., 2006	ForestGALES
Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco)	FR Database[1]	United Kingdom	40	Nicoll et al., 2006	ForestGALES
Noble fir (*Abies procera* Rehder)	FR Database[1]	United Kingdom	16	Nicoll et al., 2006	ForestGALES
Balsam fir (*Abies balsamea* (L.) Mill.)	Bespoke tree-pulling[2]	Canada	41; 80	Ruel et al., 2000; Achim et al., 2005	ForêtVENT[3]
Grand fir (*Abies grandis* (Douglas ex D. Don) Lindley)	FR Database[1]	United Kingdom	40	Nicoll et al., 2006	ForestGALES

Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.)	FR Database[1] / Bespoke tree-pulling[2]	United Kingdom / Canada	44; 20	Nicoll et al., 2006; Byrne and Mitchell, 2007	ForestGALES_BC[5]
Western redcedar (*Thuja plicata* Donn ex D. Don)	FR Database[1] / Bespoke tree-pulling[2]	United Kingdom / Canada	8; 23	Nicoll et al., 2006; Byrne and Mitchell, 2007	ForestGALES_BC[5]
Japanese cedar (*Cryptomeria japonica* (L.f.) D.Don)	Bespoke tree-pulling[2]	Japan	10	Kamimura, 2007	ForestTYPHOON[6]
Japanese cypress (*Chamaecyparis obtuse* (Sieb. Et Zucc.) Endl.)	Bespoke tree-pulling[2]	Japan	9	Kamimura, 2007	ForestTYPHOON[6]
Blue gum (*Eucalyptus globulus* Labill.)	Bespoke tree-pulling[2]	Spain	24	Locatelli et al., submitted (Chapter 3 of this Thesis)	ForestGALES

[1]FR (Forest Research) Database contains tree-pulling data collected in Britain between 1960 – 2000; [2]Bespoke tree-pulling done for the purpose of parameterisation of ForestGALES; [3]ForêtVENT is a version of ForestGALES parameterised for conifer species growing in Quebec, Canada. [4]Trees not actually pulled: parameters taken from Japanese Larch data in FR Dataset. [5]ForestGALES_BC is a modified version of ForestGALES that calculates the stability of individual trees from data on wind speed and direction, and incorporates information on upwind neighbouring stands (for a thorough description see Byrne and Mitchell, 2013). [6]ForestTYPHOON is a version of ForestGALES adapted for Japanese cedar and Japanese cypress growing on brown earth soils in Japan using field and inventory data.

1.5.1 Sitka spruce

The large number (1,155) of winched Sitka spruce (*Picea sitchensis* (Bong.) Carr.) trees in the FR database as shown in Table 1.2 reflects the predominance of this species in British conifer forests. Sitka spruce is native to North-Western America, ranging between Alaska and California (Mason and Perks, 2011). It was first introduced in Europe in the 19th century, and because of its suitability to local climatic and environmental conditions it was adopted for extensive afforestation in the British Isles during the first half of the 20th century (Mason, 2007; Ni Dhubhain et al., 2001), where it is now the predominant species, covering more than 1 M ha (Mason and Perks, 2011). In Great Britain, intensively managed forests of Sitka spruce represent 50% of the country's conifer forests (Mason, 2007), covering 29% of the total forest area (Hale et al., 2004). The species' suitability for commercial forestry in the UK is due to its tolerance to wind exposure and to soils with high moisture content and low nutrients (Mason and Perks, 2011). Sitka spruce is a fast growing species with ability to produce high yields (British average: 14 $m^3 ha^{-1} y^{-1}$; maximum: >24 $m^3 ha^{-1} y^{-1}$) which made it further attractive for commercial purposes (Mason, 2007; Mason and Perks, 2011). Recently, European forest management practices have been moving towards an approach more representative of natural conditions, called "Continuous Cover Forestry" (CCF; see Mason (2015) for a thorough review of CCF practices in Sitka spruce planted forests). While the benefits of such an approach (Stokes and Kerr, 2009) are believed to be manifold (e.g. increased biodiversity, mitigation of climate change effects on forests), structurally more complex stands may result in higher aerodynamic roughness and hence wind loading on trees. In upland Britain, wind damage to Sitka spruce in the second half of the 20th century was extensive (Fraser and Gardiner, 1967; Mackenzie and Martin, 1971). As a consequence, research in Britain on the potential for mitigation and management of wind damage focussed primarily on Sitka spruce (Dunham and Cameron, 2000; Fraser and Gardiner, 1967; Gardiner and Quine, 200; Mason, 2007; Mason, 2008). For instance, the large number of winched Sitka spruce trees in the FR Database (Fraser and Gardiner, 1967; Nicoll et al., 2006), and the studies of wind loading on Sitka spruce trees (Gardiner, 1994; Stacey et al., 1994) were motivated by the extensive adoption of this species in Northern Britain. Therefore, it was natural that the core of ForestGALES was built around data collected during these experiments (Gardiner and Quine, 2000).

1.5.2 Maritime pine

Maritime pine (*Pinus pinaster* Ait.) is a commercially important plantation species in the European South-West, especially Portugal and France. It is primarily used for the production of timber pulp, and biomass for bioenergy (Khuder et al., 2007; Moreaux et al., 2013; Shaiek et al., 2011). Charcoal and pollen analyses show that this species has been present in the central and North-Eastern regions of Portugal since ~30,000 BC, and that by the Bronze Age it had spread to the North-West of the country (Figueiral, 1995). There, it remained the major source of sawmill timber through the first decade of the 21st century despite its well-known tendencies to grow sinuous and flexuous stems (Machado and Cruz, 2005). These are responsible for the poor quality grading of its timber (Ba et al., 2010). Currently, Maritime pine is the second most abundant forest tree species in Portugal, covering ~23% of mainland Portuguese forested areas (Águas et al., 2014). The typical rotation lengths of Maritime pine in Portugal and France are similar and depend on the intended use of the extracted wood (from 8 - 12 years for pulp and bioenergy to 60 years for high grade timber) (Margot Régolini, personal communication; Trichet et al., 2008). Timber yields are similar between the two countries and normally range between 8 – 11 $m^3\ ha^{-1}\ y^{-1}$ (Trichet et al., 2008). Portuguese plantations cover an area around 1 M ha which translates to national yields of about 6 $Mm^3\ y^{-1}$ of timber (Machado and Cruz, 2005). In France, the vast majority of Maritime pine plantations are located in the Aquitaine region in the South-West. About 7% of French forested areas (> 890,000 ha) is dedicated to Maritime pine, providing ~16% of the French timber and pulp production (~7.4 Mm^3, Cucchi and Bert, 2003; Cucchi et al., 2005). As discussed in Section 1.2, damage to Maritime pine caused by storms Martin (1999) and Klaus (2009) was extensive. A triptych of research papers on Maritime pine's wind-resistance in Aquitaine was produced in the early 2000s (Cucchi and Bert, 2003; Cucchi et al., 2004; Cucchi et al., 2005). In these papers, the authors analysed the effect of a range of silvicultural practices to reduce the risk of windthrow after the large losses caused by storm Martin (1999), which amounted to 5 times the annual harvest of softwood (Gardiner et al., 2010). The authors found that windthrow was less abundant in dense stands with homogeneous trees than in more sparse stands, where leaning pines were predominant (Cucchi and Bert, 2003), suggesting mutual support between trees and reduced wind penetration in the stands; in addition to this, trees growing in dry soil conditions, in the absence of a hardpan layer, were more prone to stem breakage than uprooting, suggesting better anchorage. The importance of soil properties in the development of the root system of Maritime pine and

the species' inability to penetrate a hardpan have been confirmed by Danjon et al. (2005). The authors report mean rooting depths of about 1m for mature trees, most of which extended until the depth of the hardpan layer. Cucchi et al. (2004) also found that trees at the stand edge had 20% more resistance to overturning than inner trees due to a larger soil plate, especially on the windward side, showing some adaptation to wind. Cucchi et al. (2005) parameterised ForestGALES for Maritime pine and used it in their simulated stands, showing that the model was able to confirm trees' stronger tendency to overturning rather than breakage, and the detrimental effect of shallow rooting depth with regards to the critical wind speeds. Chapter 4 uses ForestGALES to compare the vulnerability to wind damage between Maritime pine and *E. globulus*.

1.5.3 *Eucalyptus* spp.

Currently, one of the most widely adopted plant genera for commercial plantations is the *Eucalyptus* genus, which is primarily used for the pulp and fibre board industries (Diaz-Balteiro and Rodriguez, 2006), although grading of its wood also allows for use as timber (Gardiner and Moore, 2014). Plantations of *Eucalyptus* spp. currently provide 50% of the world's wood fibre (FAO, 2007). The genus was introduced at the beginning of the 20th Century to Brazil, which is the country with the most extensive and intensive management of Eucalypts (Campoe et al., 2012). The Brazilian planted area of Eucalypts is approximately 4.7 M ha (ABRAF, 2011), resulting in a production of paper pulp of ~7.5 M tonnes y^{-1} (Diaz-Balteiro and Rodriguez, 2006), equivalent to almost 100% of the country's wood fibre production (Sedjo, 1999). The attractiveness of this genus for commercial purposes is due to its fast growth rates, good stem form, good adaptability to different environmental conditions, predisposition to hybridisation and cloning, and natural tendency to sprout vigorously when coppiced, which decreases planting costs (Campinhos, 1999; Giménez et al., 2013; Goncalves et al., 2008). In Brazil, under optimal climatic conditions and management practices, the productivity of *Eucalyptus* spp. ranges from yields of 520 m^3 ha^{-1} on highly productive sites, to 179 m^3 ha^{-1} on less productive areas (quoted yields are for stocking densities of 1660 trees ha^{-1}) (Diaz-Balteiro and Rodriguez, 2006). Mean annual increment (MAI) under current silvicultural practices is typically around 40 m^3 ha^{-1} y^{-1} (Binkley and Stape, 2004), with recorded maxima of 90 m^3 ha^{-1} y^{-1} in small trial plots (Eldridge et al., 1994), while rotation length is typically 6 – 7 years (Diaz-Balteiro and Rodriguez, 2006). Currently, the most

widely used species in Brazil are clonal varieties of *Eucalyptus urophyll*a S.T. Blake, *Eucalyptus grandis* W.Hill ex Maiden, and a hybrid of the two, commonly referred to as *Eucalyptus urograndis* (Almeida et al., 2004). These species have largely replaced *Eucalyptus globulus* (Labill.) as the favoured tree species for pulp plantations in Brazil because of their larger yields and elevated genetic plasticity (Campinhos, 1999).

Like most species of the genus *Eucalyptus*, *E. globulus* is native of Australia, where it is the major plantation species for pulpwood production (Candy, 1997), covering an area of more than 0.5 M ha (Wang et al., 2007). *E. globulus* has rapidly become an important commercial species in temperate areas due to its fast growth, high pulp quality, and suitability to temperate climates (Campinhos, 1999; Sasse and Sands, 1997). In Europe, this species was introduced in the 19th century (Leslie et al., 2011), and has been increasingly used in commercial plantations in the Iberian Peninsula for the production of biomass for pulp and bioenergy (Diaz-Balteiro and Rodriguez, 2006; António et al., 2007). The high density of its wood makes this species particularly sought after for bioenergy purposes (the Forest Products Commission of Western Australia reports a typical value of green wood density of 1040 kg m^{-3}). In Portugal, *E. globulus* trees are planted on ~812,000 ha, i.e. over 26% of the nation's forested area (Águas et al., 2014), having recently surpassed Maritime pine as the predominant tree species in Portugal (Dias and Arroja, 2012). In Spain, *E. globulus* plantations are mostly concentrated in the Northern regions of Asturias and, especially, Galicia (Riesco-Muñoz, 2004). In the Iberian Peninsula the typical rotation length is 10 – 12 years and yields range between 10 m^3 ha^{-1} y^{-1} and 50 m^3 ha^{-1} y^{-1} (António et al., 2007; Riesco-Muñoz, 2004), with MAI of 10 – 15 m^3 y^{-1} (Diaz-Balteiro and Rodriguez, 2006). In South-Western France, plantations of a hybrid of *Eucalyptus gunnii* (Hook.) and *Eucalyptus dalrympleana* (Maiden) have been present for the last 30 years, mainly for production of biomass for pulp and bioenergy (AFOCEL, 2004; Moreaux et al., 2013). Establishment trials of this hybrid, named *Eucalyptus gundal*, have been successful (Gabrielle et al., 2013). In fact, in temperate areas with summer periods of low precipitation and moderately cold winters, its good tolerance to water scarceness and its cold-hardiness to -12^{o}C, especially past the juvenile stage, are advantageous traits (Melun, 2011; Terreaux, 2000). While *E. globulus* is not as cold-hardy (tolerant until -6^{o}C) as *E. gundal* and its parent species, trial plots of *E. globulus* have performed well on coastal areas of Ireland (Neilan and Thompson, 2008).

Eucalyptus spp. require large amounts of water to sustain their rapid growth, and due to the fact that they are perennial (i.e. they do not shed leaves during the winter, as opposed to most hardwood species) (Drake et al., 2012). Indeed, water shortage in the summer months is the main limitation to their growth in Northern Iberia (Fabião et al., 1995). Their large rooting system, often equipped with a central tap-root, is able to tap into aquifers located at great depths, which has given rise to much controversy about their role in water shortages experienced by other tree species and adjacent crop fields (Drake et al., 2012; Kardell et al., 1986). In their review of the maximum extent of tree roots, Stone and Kalicz (1991) report a depth of over 4m, and a radius of over 5.8m, for the rooting system of 10-years old *E. globulus* trees that had been excavated. Despite the limited research on the response of rooting systems of Eucalypt trees to the presence of soil hardpan layers, some indication exists that species of this genus have sufficient root vigour to penetrate clayey sub-soils with densities up to 2.0 g cm^{-3} (Robinson et al., 2006). These figures would suggest optimal anchorage of *Eucalyptus* spp. to counteract windstorms. Similarly, the high density of the wood of Eucalypts might indicate low vulnerability to stem breakage, as green wood density is normally positively correlated with the Modulus of Rupture of green wood (Niklas and Spatz, 2010). Unfortunately, however, while research on the risk of pest and fire damage to Eucalypts is at an advanced stage, with vulnerability to fire similar to that of Maritime pine (e.g. Moreira et al., 2009; Águas et al., 2014), data on wind damage to Eucalypts is scarce. Studies of the effect of wind on Eucalypt trees are few and rarely focus on wind damage. McArthur et al. (2010) show a decrease of tree height growth and leaf area in saplings of *Eucalyptus tereticornis* Sm. exposed to constant wind speeds of 3 m s^{-1} for three hours a day during a period of 6 weeks. Mokotedi et al. (2010) performed vertical pulling experiment on saplings of the hybrid *E. grandis* X *Eucalyptus nitens* (H.Deane & Maiden), confirming the role of the tap-root in providing resistance to uprooting. However, their experimental setup is not representative of the wind loading on trees during a windstorm, as described in Section 1.1. In their 12-months study on tree vulnerability to wind damage in urban environments, James et al. (2006) report that the complex canopy structure of *E. grandis* and *E. tereticornis* provided the trees with a dynamic damping that reduced the dangerous harmonic sway motions that increase the risk of wind damage, although in their study the authors only investigated the response of individual trees rather than in the context of a forest stand.

However, little detailed information is available about the vulnerability of Eucalypts to wind damage, or about the extent of wind damage occurring in Eucalypt stands. Trabado (2009)

reports that volumes of timber damaged by storm Klaus (2009) in the North-Western Spanish region of Galicia ranged between 1.2 and 1.8 Mm^3, 45% of which were from *E. globulus* trees. Despite the mean wind speeds experienced in the Iberian Peninsula during storm Klaus did not differ greatly from those in Aquitaine (Liberato et al., 2010), which resulted in catastrophic losses in maritime pine plantations (see Section 1.2), damage to Eucalypt stands in Spain was minor, and no reports of wind damage exist in Portugal. Detailed data about tree and stand characteristics in the affected Eucalypt forests in Galicia are not available. In Uruguay, two violent tropical cyclones in 2009 (the first in January, the second in November) caused damage to approximately 10% of a 27,000 ha Eucalypt private plantation, corresponding to financial losses of 10 M US$. The fact that in the decade preceding such events no wind damage to the plantation had occurred made these massive losses unpredictable from an historical point of view (Phil Cottle, personal communication). For this event, data on species, tree and stand characteristics, and wind speeds responsible for the damage are not available. However, Campinhos (1999) reports on the use of *E. globulus* and *E. grandis* in Uruguayan plantations. Only three papers exist in the literature (Williams and Douglas, 1995; Gerrand et al., 1997; Chen, 2003) where wind damage to Eucalypt stands are reported together with some data on tree and stand characteristics, although the wind speeds responsible for the damage are available only in the latter. These three studies are extensively discussed in Chapter 3, where they are adopted for the evaluation of the parameterisation of ForestGALES for *E. globulus*.

The importance of being able to estimate the risk of wind damage to commercial plantations in general and Eucalypt plantations in particular is all the more evident when the pressure on natural forests to provide ecosystem services (e.g. biodiversity, soil and water conservation) is considered. Gardiner and Moore (2014) advocate for a separation of types of forested areas (i.e. natural *vs* planted, accordingly managed with silvicultural practices appropriate for the intended uses), to ensure that provision of ecosystem services from natural forests, and harvest of timber and wood products from planted forests, can coexist in a way that is environmentally sustainable and able to meet the increasing demands of global markets. In fact, by maximising the likelihood that the productivity potential of planted forests is realised, the requirement for extracting timber and other wood products from natural forests can be greatly reduced (Sedjo, 1999). The importance of Eucalypt plantations for the global pulp and bioenergy markets is already very large, and likely to increase in the future (Gardiner and Moore, 2014). Developing the methods to reduce their vulnerability to wind damage is

paramount to prevent future catastrophic losses. Similarly, the lack of such methods might dissuade future investments in Eucalypt plantations.

1.6 Sensitivity analysis of mathematical models

For the creation and application of mathematical models, it is important to know the sensitivity of the model's outputs to variations in the inputs and in the parameters used in the model. That is, being able to apportion the uncertainty in the output of a model to different sources of uncertainty in the inputs (Saltelli et al., 2004). This information can be used in several ways, e.g.: for model calibration (Ratto et al., 2001); to focus resources when gathering data, such as in fieldwork (Bastidas et al., 1999); to uncover inadequacies in the adopted approaches to the modelling of natural or man-made processes (Saltelli et al., 2008); to identify regions in the space of the inputs that result in critical realisations of the model (Cariboni et al., 2007); to produce models that are more parsimonious, robust, and defensible when confronted with technical and scientific controversies (Saltelli and Funtowicz, 2014). Despite the importance and potential of its applications, sensitivity analysis of mathematical models is a practice often overlooked or performed perfunctorily (Saltelli et al., 2006). However, in light of the substantial advancements that have been made in this field of research in recent years (Borgonovo and Plischke, 2016), this negligence is seldom, if ever, justified. When performed appropriately (Saltelli and Annoni, 2010), sensitivity analysis is an invaluable tool for modellers, practitioners, and decision-makers, as it can provide insight on the inner workings of complex models, and ensures transparency in the applications of these models and communication of the outputs to stakeholders (Tarantola et al., 2002). Particular care must be taken when models are used to drive policies and inform stakeholders and decision-makers (e.g. for a sharp critique of the Stern review (2006) from the point of view of practitioners of sensitivity analysis, see Saltelli and D'Hombres, 2010).

1.6.1 Approaches to sensitivity analysis: "local" methods:

A number of techniques to perform sensitivity analysis exist. These can be typically divided into two groups, according to how the input space is explored (Saltelli et al., 2000). Commonly used techniques such as sigma-normalised derivatives of an output versus an input belong to the class of "local" sensitivity analysis methods, whereby only one point in

the input space is considered (typically the mean). While derivative-based approaches can be intuitively thought of as an appropriate mathematical definition of sensitivity of an output with respect to an input, they are burdened with a number of issues (Saltelli et al., 2008). Firstly, these methods are only warranted when an output is linear with respects of the input for which the sensitivity measure is calculated, so that the measure can be confidently extrapolated to other points (e.g. with first-order point derivatives); this is seldom the case with complex models, especially environmental ones, where non-linearities typically abound. Secondly, with local approaches the uncertainty of an input is not properly represented, as the sensitivity measure is computed only at one point which, as representative of the input as one might believe (mistakenly or otherwise), does not contain a measure of the uncertainty of that input. Similarly, sometimes local sensitivity analysis is performed by perturbing the variables, one at a time, by some set amount (e.g. increasing or diminishing the mean by a given percentage). This is the case for ForestGALES, for which only a local sensitivity analysis has been performed (Gardiner et al., 2000). Thirdly, local sensitivity measures do not account for the presence of interactions between inputs, as they are calculated for one input at a time. Despite these problems, derivative-based methods of sensitivity analysis are the method most commonly encountered in the literature (see Saltelli et al. (2006) for a review of modelling papers published in Science where the authors submitted their models to SA). For instance, guidelines of the Intergovernmental Panel on Climate Change advocate the use of sigma-normalised derivatives for SA of inventories of greenhouse gases (IPCC, 1999; IPCC, 2000).

1.6.2 "Global" methods of sensitivity analysis

A solid alternative to local methods is represented by a family of techniques normally referred to as "global". This term indicates that the attention is focussed on the entire input space, rather than single points within the range of single inputs. This approach is based on the idea that, citing Saltelli et al. (2008), "*a handful of data points judiciously thrown into* [the input] *space is far more effective, in the sense of being informative and robust, than estimating derivatives at a single data point in the centre of the space*". Global sensitivity analysis (GSA) methods allow practitioners to overcome the limitations of local methods. These approaches are said to be "model-free", in that they do not make any assumptions about model linearity or monotonicity. The most powerful GSA methods are those based on

the decomposition of the variance of the output of a model into summands of conditional variances of increasing dimensionality (Saltelli et al., 2008). Of the variance-based GSA methods, the most powerful and most commonly adopted in the literature is that of Sobol' (2001). This method is adopted in this thesis for the sensitivity analysis of ForestGALES presented in Chapter 5, and partially in Chapter 3, and as such it is extensively described in the relevant subsections of these Chapters. In Chapter 2 I briefly describe other GSA methods found in the literature. Using the variance of the inputs, rather than the mean, has the advantage of representing the uncertainty associated with the inputs. Finally, variance-based GSA methods are not restricted to calculating sensitivity measures for one input at a time, as they are able to decompose the variance of the output into variances conditional to as many inputs as desired.

The main disadvantage of GSA methods is the high computational cost required for the calculation of the sensitivity measures (e.g. Saltelli et al., 2009). These are estimated numerically with Monte Carlo techniques, whereby a large sample (in the region of a few hundred to several thousands) is generated from the probability distribution functions (PDFs) of the inputs to describe the inputs variability, which is then propagated to the outputs through executions of the model. Therefore, GSA techniques are not practical for large, complex models such as Large Eddy Simulation models, which are very time-consuming and require extensive computational power. In this case, qualitative GSA methods such as that of Morris (1991) should be used. Whilst GSA techniques, and especially the method of Sobol', are quite robust with regards to the accuracy with which the inputs are described with PDFs (Iooss and Lemaître, 2014), it is advisable to exercise particular care when choosing the appropriate PDF and the values of its parameters (e.g. the mean and standard deviation for Gaussian distributions). For this reason, in the sensitivity analysis of ForestGALES presented in Chapter 5, Sitka spruce is used as a benchmark species to evaluate the results obtained for maritime pine and *E. globulus*. In fact, the abundant Sitka spruce data collected in the FR database provide confidence that the PDFs of the input variables can be reliably calculated to fit the data.

1.6.3 Settings for global sensitivity analysis

As mentioned at the beginning of Section 1.6, sensitivity analysis can serve a number of purposes. Before subjecting a model to sensitivity analysis, it is therefore strongly

recommended that the scope of the analysis is accurately framed, so as to identify the most appropriate setting for the analysis. Four settings are commonly adopted when performing GSA: Factor Prioritisation (FP), Factor Fixing (FF), Factor Mapping (FM), and Variance Cutting (Saltelli et al., 2004). The first three are used in this thesis and are briefly introduced here. In GSA parlance, the term factor is used to describe any source of variation in the model, and therefore can include input variables as well as model internal parameters. In the GSA of ForestGALES presented in Chapters 3 and 5 I focus on the model input variables in order to provide guidelines for practical applications of ForestGALES, for the benefit of the end users as well as of the wind damage modelling community.

1.6.3.1 The Factor Prioritisation (FP) setting

The FP setting is adopted when the aim of the analysis is to identify those variables which, when fixed to their true value, result in the largest reduction of the output variance. In environmental modelling, it is not possible to talk about "true" values of a variable that describes an element of the natural world (e.g. tree height), because of the inherent variability of the natural world. In these cases, one would focus on maximally reducing the uncertainty of a variable. In the case of ForestGALES, this setting is adopted to identify the variables on which sampling resources should be focussed for practical applications of the model. For instance, should tree height be identified as a highly significant variable, a forester willing to estimate the critical wind speeds and the risk of wind damage to their forest stands as accurately as possible should focus their resources to the accurate measurement of the height of the tree. One solution in the case of large forest stands would therefore be to obtain accurate tree height data using LiDAR technology (Suarez et al., 2005).

1.6.3.2 The Factor Fixing (FF) setting

The FF setting aims at identifying those variables which, when allowed to freely vary over their range, have a negligible impact on the variance of the output. Therefore, the variables can be fixed at a nominal value within their range without affecting the output variance significantly. This information can be used in several ways: it can help simplifying a model, by flagging those variables that can be confidently removed; it can advise on better resource management, as non-influential variables need not to be sampled with high accuracy (they

might not need to be sampled at all if the sensitivity measures are close to zero); lastly, it can alert practitioners on the inadequate representation of a process characterised by non-influential variables. This is especially relevant to process-based models which aim at providing a law-driven description of natural events. With regards to the hypothetical case of tree height being non-influential to the output of ForestGALES, for instance, the results of the FF setting would prompt modellers to question the structure of the model, since tree height is known to be one of the main drivers of the risk of wind damage in the real world (e.g. Petty and Swain, 1985; Kohnle et al., 2003).

1.6.3.3 The Factor Mapping (FM) setting

The FM setting is based on Regionalised Sensitivity Analysis, a form of Monte Carlo filtering, whereby the analyst is interested in the identification of the variables, or group of variables, which are most responsible for realisations of the model in a specific region of the output space (Hornberger and Spear, 1981). This is especially useful when the output is expressed in the form of risk, or probability, and critical thresholds can be identified. For the GSA of ForestGALES in Chapter 5 I have set the threshold for the probabilities of breakage and overturning at 10%. That is, for each type of damage I have divided the output space in two regions: one which contains the model realisations that fall below probabilities of damage of 0.1, and a complementary region for probabilities that exceed this critical value. By mapping the model realisations of the two regions back to the input space of each variable, influential variables can be identified.

1.7 Thesis objectives and overview

In light of the concerns expressed in the previous sections, three objectives are set for this thesis:

1. To parameterise and evaluate the performance of the wind damage risk model ForestGALES for *Eucalyptus globulus* (Labill.). It is paramount to be able to model the risk of wind damage for this species for two reasons: a) Historical data on wind damage to *E. globulus* are not available; b) The commercial importance and the planted area of this species are already large and projected to increase in the future;

2. To use ForestGALES model simulations to compare the susceptibility to wind damage of *E. globulus* and *Pinus pinaster* (Ait.). *P.pinaster* is an important plantation species which in recent years has suffered extensive wind damage in the Aquitaine region (SW France). Because of the similarities between the habitat range and intended uses of the two species, I investigate whether *E. globulus* might be a substitute species for maritime pine in the region, from the point of view of the vulnerability to wind damage;
3. To identify the input variables of ForestGALES that are most important for the calculations of the critical wind speeds for stem breakage and tree uprooting and the related probabilities of damage, and those input variables that can be confidently set to a value within their range without significantly affecting the variability of the model outputs. The findings can then be used for four purposes: a) recalibration of ForestGALES; b) re-evaluation of the model structure with regards to the currently non-influential variables; c) large scale applications of the model, and d) improved resource management for the acquisition of accurate model input data.

Three individual paper chapters, each addressing one of the objectives listed above, compose the core of this thesis. These are preceded by a general description of the materials and methods used for this study, which can be found in Chapter 2. Additional details about the methodologies used in each of the paper chapters are found in the relevant subsections of each chapter. The thesis concludes with a thesis summary and conclusion chapter, where the findings of the paper chapters are brought together to discuss the thesis objectives.

Chapter 3 – Describes the parameterisation and evaluation of ForestGALES for *E. globulus* to address Objective 1. Fieldwork, in the form of tree-pulling experiments, was performed on a stand of *E. globulus* trees growing in the North-Eastern Spanish region of Asturias and is described in this Chapter. The scarcity of published studies on wind damage to *Eucalyptus* spp. in general, and *E. globulus* in particular, meant that only an evaluation of this parameterisation could be performed. To this aim, ForestGALES simulations were performed for a range of stocking densities that included that of the fieldwork stand, as well as those of three papers that presented sufficient data to make a preliminary assessment of model performance. A partial global sensitivity analysis of the adapted model is presented, where the upwind gap is treated as a "brown edge", i.e. a recently established stand edge.

Chapter 4 – Makes use of the parameterisation of ForestGALES performed in Chapter 3 to address Objective 2. This is done by a comparison of the damaging critical wind speeds and probability of damage between simulated stands of *E. globulus* and *P.pinaster* "grown" under environmental conditions typical of the South-Western French region of Aquitaine. Two effects are estimated: (a) that of a windward gap and (b) that of different growth rates (x2) and rooting depths typical of the area (x2). The two species and the geographical area were chosen because of the large damage suffered by *P.pinaster* during storms Martin (1999) and Klaus (2009), as opposed to the limited damage to *E. globulus* in regions of the neighbouring Iberian Peninsula, where the recorded wind speeds during storm Klaus were similar to those in Aquitaine. The maximum mean wind speeds of the two storms were used as a reference. The relevance of the comparison is evaluated and discussed in regards to tree height, age of the trees, and stand productivity, together with the potential for species change in the region.

Chapter 5 – Presents the results of a sensitivity analysis of ForestGALES to provide a response to Objective 3. Global sensitivity analysis (GSA) techniques are used to investigate the contribution of the user inputs of ForestGALES to the variation in the values of the critical wind speeds for breakage and overturning, and the associated probabilities of damage, calculated with Monte Carlo methods. Large inputs datasets are generated from probability density functions of the input variables using the quasi-random method of Sobol', to ensure quicker convergence to the values of the sensitivity measures. Because of the correlation between input variables, a recently developed GSA method for correlated variables, based on the method of Sobol', was used. The study presented in this Chapter is the first instance of the GSA method for correlated variables being applied to a complex mathematical model. A detailed description of these methods is given in Chapters 2, 3, and 5. Results for three important plantation species are compared: *P. sitchensis*, *P. pinaster*, and *E. globulus*. One important difference with the GSA performed for the *E. globulus* parameterisation in Chapter 3 is the nature of the upwind gap, which in this Chapter is treated as a "green" edge. That is, a stand edge which has not been recently created. The significance of the findings is discussed in regards to the model's structure, the sampling requirements of the variables, and the applicability of the model for large geographical areas.

Chapter 6 – Brings together the findings discussed in each of the preceding chapters to discuss them within the scope of the thesis, as described by the three thesis objectives. Ideas and requirements for future studies are discussed and presented in detail.

Despite the uncertainties associated with predictions of future weather patterns influenced by climatic changes (IPCC, 2014), recent projections of the effects of the increase of oceanic surface temperatures suggest that future weather will be characterised by more frequent and intense damaging storms (Haarsma et al., 2013). These weather shifts will constitute serious challenges for the management of the world's ecosystems, and particularly to forests, which are vulnerable to damage from strong winds (Schelhaas et al., 2010). These challenges require that our understanding of the dynamics and impacts of wind damage to forest ecosystems are improved, and extended to future weather patterns and to tree species whose abundance and extent of geographical distribution are likely to increase to meet the world's demands of forest products (Gardiner and Moore, 2014). This is all the more relevant when the projected effect of increasing temperatures on the geographical optima of the ecological niches of trees is considered (e.g. Cheaib et al., 2012). From these considerations, it follows naturally that statistical models of the risk of wind damage to forests will not provide us with reliable projections of wind damage. In fact, the prediction ability of statistical model is typically very low for conditions that differ greatly from those of the data that these models are built on (Lanquaye-Opoku and Mitchell, 2005). Therefore, we need solid, applied tools that are applicable over a wide range of ecological and climatic conditions. Process-based models are obvious candidates for this task. For these reasons I have investigated and modelled the vulnerability to wind damage of *E. globulus*, the first commercially highly important species to be added to the species list of process-based wind-risk models. Similarly, I firmly believe that to apply a model without knowing it "intimately" is a potentially dangerous practice, particularly when the model is used for decision-making. This is why I have gone through the meticulous investigation of the inner workings of ForestGALES with the global sensitivity analysis methods that form such a large part of my work.

Chapter 2 Materials and Methods

This section gives an overview of the ForestGALES wind risk model, including the fieldwork operations necessary for the parameterisation of a new species into the model. A general discussion about sensitivity analysis of model outputs is also presented in this section. Additionally, more detailed methodologies of the work performed for this thesis are provided in the respective paper chapters: Chapter 3 for the parameterisation of ForestGALES for *E. globulus*; Chapters 3 and 4 for the applications of ForestGALES; and Chapters 3 and 5 for the sensitivity analysis of the model.

2.1 The ForestGALES model

ForestGALES is a quantitative, semi-mechanistic, probabilistic and predictive model of wind risk damage to forest assets. It is semi-mechanistic - or hybrid - in that some components of the model that describe tree characteristics, and the calculations of the uprooting moment, are based on experimental data rather than on engineering principles. As discussed in the introduction, the model has been parameterised for the most common British conifer species (Gardiner et al., 2008), as well as for some conifer species in Canada, Denmark, France, Japan, and New Zealand (Byrne, 2005; Cucchi et al., 2005; Kamimura et al., 2008; Mikkelsen, 2007; Moore and Somerville, 1998; Ruel et al., 2000). In Chapter 3 of my thesis I will present the first instance of the parameterisation of a broadleaf species, *E. globulus*.

ForestGALES requires a small set of inputs. Table 2.1 lists the various inputs and the corresponding units. These are in turn discussed below and include tree-stand characteristics and an estimate of the prevailing wind climate.

Table 2.1 - ForestGALES input variables.

Variable name	Variable description	Units	Comments
Top height	Height of the tallest tree(s) in a stand	m	If top height data is not available, mean tree height can be used
Dbh	Mean diameter at breast height (1.3m)	cm	Converted to meters in model calculations
Sph	Stocking density	Number of stems ha^{-1}	Alternatively: mean tree spacing
Soil type	Predominant soil type in the stand	n/a	Soil grouping in ForestGALES shown in Table 2.2
Rooting depth	Predominant depth of rooting system in the stand	n/a	In the version of ForestGALES used in this thesis, Rooting depth has 3 levels: 1=shallow; 2=medium; 3=deep (as in ForestGALES 2.1)
Gap size	Size of largest upwind gap adjacent to the stand	m	Used for calculation of mean wind loading
DAMS	An estimate of the prevailing winds	n/a	Alternatively: Weibull A and K parameters of distribution of prevailing winds

Tree and stand characteristics used as inputs include: height of the tallest tree(s) in a stand (alternatively: mean tree height if tallest tree is not available), mean tree diameter, stocking density, predominant soil type, and mean stand rooting depth. Information on the size of any upwind gap adjacent to the stand is also necessary to calculate the effect of wind gusts on the trees at increasing distance from the stand edge. For British sites, the prevailing wind climate is normally described with DAMS scores (Detailed Aspects Method of Scoring). These describe the windiness of a site based on topographic characteristics, and are only available for Britain (Quine and White, 1994). Alternatively, shape and scale parameters of a Weibull distribution fitted to time series of local wind speed data can be used when DAMS scores are not available (Quine, 2000). Since most calculations in the model are based on species-specific values and allometric calculations, tree species serves as a trigger and must be specified together with the other inputs. The version of ForestGALES used in my experiments is sometimes referred to as the “roughness” method (Hale et al., 2015). In this approach, the wind momentum stress (Raupach, 1994), acting on the rough canopy surface of a stand, is partitioned between trees to calculate the stress on individual trees. These calculations are then corrected for the effect of gust winds. Recently, Hale et al. (2012) have proposed an alternative method, referred to as the “turning moment coefficient”, which removes the need to account for gust winds by focussing on single trees characteristics. Because this latter

method is not used in my experiments, the following sections apply to the traditional "roughness" method only. ForestGALES is composed of two main modules: GALES, where the critical wind speeds for stem breakage and uprooting are calculated, and a "Wind Climate" module (WCM), where the probabilities of damage and the return periods of damaging storms are calculated from information on the local wind climate and the critical wind speeds calculated with GALES.

The rationale of the model can be summarised in 3 main points:

1. the model estimates the moments required for breaking or uprooting the average tree in the stand (GALES module);
2. the Critical Wind Speeds (CWS) to generate such moments are calculated (GALES module);
3. the probabilities of exceeding these CWS under the local wind climate are estimated (Wind Climate module).

The following diagram shows a simplified resume of the structure of the model from the viewpoint of the user input variables. The equations numbers in the figure are found in the text throughout this section.

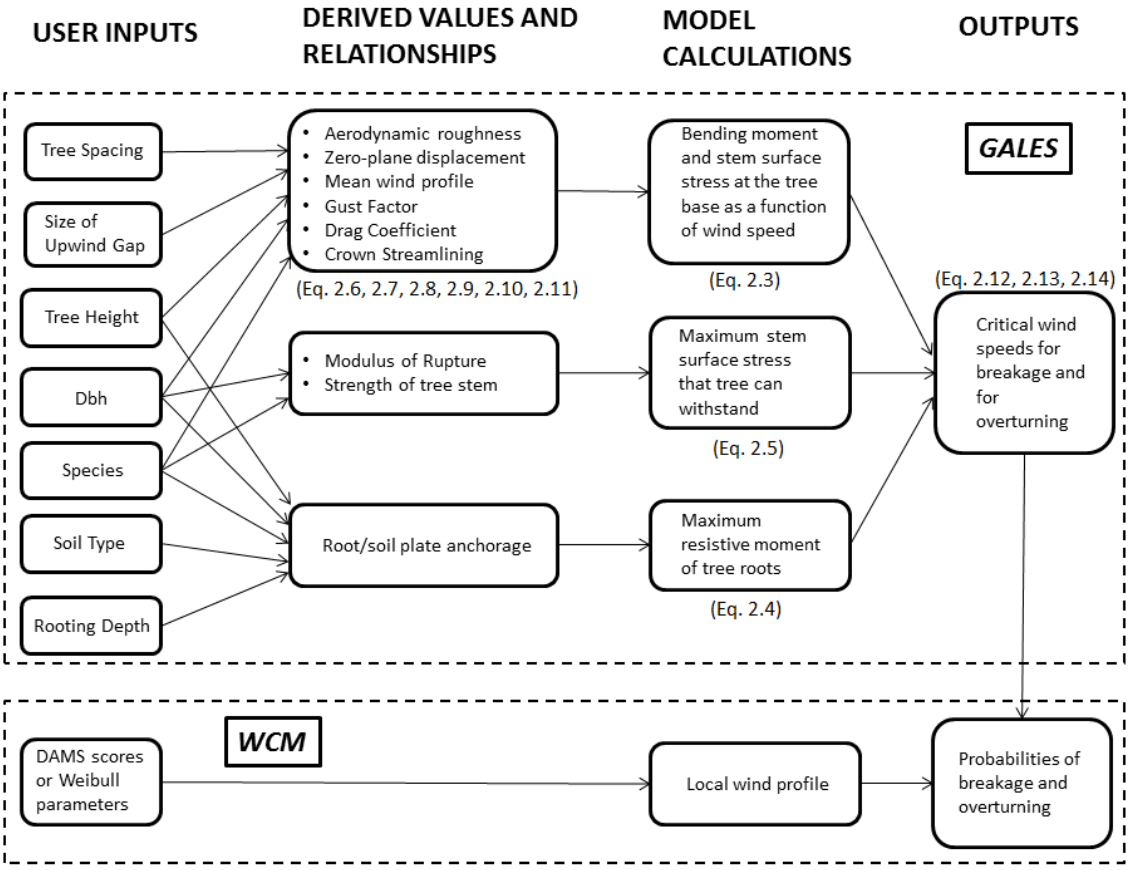


Figure 2.1 - Basic schematic of the structure and rationale of ForestGALES (adapted from Gardiner et al., 2000). The dashed boxes delimit the two main modules that compose ForestGALES. The GALES module calculates the critical wind speeds for breakage and overturning. WCM: Wind Climate Module, where the probabilities of breakage and overturning are calculated. Equations numbers refer to the text throughout section 2.1.

2.1.1 Estimation of critical moments

ForestGALES predicts the risk of wind damage to the average tree in a stand. Hence, if top height is supplied as one of the model's inputs, the model converts top tree height to mean tree height. This is then used with dbh (diameter at breast height) in the calculations of the volume and mass of the stem and the branches. As described in section 1.1, the force to which a tree is subjected can be divided into a horizontal component, as provided by the wind action, and a vertical component, which is the result of self-loading (i.e. the mass of the crown and the stem), as well as of snow, when applicable (Gardiner et al., 2008). Throughout this section, I disregard the contribution of snow to a tree's self-loading, as this is simply treated in the model as additional weight relative to the volume of the branches. Canopy dimensions are calculated for the estimation of wind loading. Following Raupach's (1994) theory of momentum stress partitioning, the wind loading on an average tree within a stand

of a given stocking density is calculated on the assumption that the stress of the air on the canopy surface ($\tau = -\rho u_*^2$), which is a function of the latter's aerodynamic roughness, acts at zero-plane displacement height (*d* (m); Thom, 1971). In the above calculation of the stress on the canopy surface, ρ is the air density (kg m^{-3}), and u_* is the wind friction velocity (m s^{-1}). Following this assumption, Gardiner et al. (2000) and Quine and Gardiner (2007) have shown that the mean bending moment (M_{mean} (Nm)) exerted by the wind at any height *z* (m) on a tree can be calculated as a function of the average spacing between trees (*D* (m)):

$$\boldsymbol{M_{mean}(z) = (d - z)\rho u_*^2 D^2} \quad \textbf{(2. 1)}$$

Another assumption made by the model, of a logarithmic profile of wind speed above the canopy (Gardiner et al., 2000; Gardiner and Quine, 2000), allows for the calculation of the mean turning moment as a function of the canopy top wind speed u_h (m s^{-1}):

$$\boldsymbol{M_{mean}(z) = (d - z)\rho \left(\frac{D u_h k}{\ln\left(\frac{h-d}{z_0}\right)} \right)^2} \quad \textbf{(2. 2)}$$

where *k* is Von Karman's constant (value = 0.4, dimensionless), *h* is the average tree height (in m), and z_0 is the canopy roughness (in m). While the maximum wind speeds affecting a stand occur in short-lived gusts of just a few seconds, wind data standardly available for the model's calculations are in the form of maximum hourly wind speeds (Hale et al., 2015). This data-availability issue has prompted the development of a Gust Factor, using empirical relationships between mean and maximum bending moments. These relationships were first obtained with model miniature Sitka spruce trees in a wind tunnel (Stacey et al., 1994), and subsequently confirmed with real Sitka spruce trees planted at different spacing distances (Gardiner et al., 1997). The Gust Factor is then defined as the ratio between maximum turning moment and mean turning moment (Gardiner et al., 2000), using the size of an upwind gap to adjust for the increase in wind loading on edge trees when a new gap is formed. In fact, trees that are acclimated to pre-existing edges are considered to be at no greater risk than trees well inside the forest (Morgan and Cannell, 1994). The introduction of the Gust Factor, together with a factor accounting for the additional moment provided by the stem and canopy mass as the tree is swayed by the wind from its vertical axis, allows the conversion of the mean turning moment to the maximum turning moment:

$$\boldsymbol{M_{max}(z) = f_{CW}(d - z)\rho G \left(\frac{D u_h k}{\ln\left(\frac{h-d}{z_0}\right)} \right)^2} \quad \textbf{(2. 3)}$$

where $M_{max}(z)$ (in N m) is the maximum turning moment at tree height z, f_{CW} is the tree mass factor (dimensionless), G is the Gust Factor (dimensionless). Calculations of the tree mass factor follow the tree bending equations defined by Neild and Wood (1999), requiring knowledge of the mass distribution profile along the height of the tree, the wind force, and the height of the zero-plane displacement. The latter, together with the aerodynamic canopy roughness, is calculated with the method described in Raupach (1994), which makes use of a "drag coefficient" term –function of wind speed- to describe the changes in wind penetration through the tree canopy, as described in section 2.1.2.

Soil type and rooting depth data are incorporated into the model to calculate the critical uprooting moment, while the Modulus of Rupture of green wood is used in the calculation of the critical breaking moment (Gardiner et al., 2000). In the version of the model used throughout my experiments, soil types are broadly grouped on the basis of their draining potential and mineral content (Avery, 1990; Kennedy, 2002), as shown in Table 2.2. Three rooting depths (shallow: < 40cm; medium: 40cm – 80cm; and deep: > 80cm) complement the soil type data. The four soil groups and three rooting depths represent the columns and rows of a table populated with empirically derived values of the overturning moment multipliers. These multipliers (C_{reg}) are species-specific coefficients of linear regressions of total overturning moment, as measured empirically in the field, against stem weight under different soil types and rooting depths (Nicoll et al., 2006). For the first versions of ForestGALES, a large tree-pulling database (~2,000 trees) assembled by the British Forest Research Institute was used to calculate C_{reg} values for the most common conifer species in Britain (Ray and Nicoll, 1998).

Table 2.2 - Soil classification used in ForestGALES. Soil classification based on Avery (1990) and Kennedy (2002).

A	B	C	D
Freely-draining mineral soils	**Gleyed mineral soils**	**Peaty mineral soils**	**Deep peats**
Brown earth (freely-draining)	Ironpan (gleyed)	Ironpan (peaty)	Juncus (or basin) bogs
Ironpan (freely-draining)	Podzol (gleyed)	Podzol (peaty)	Molinia (or flushed blanket) bogs
Podzol (freely-draining)	Brown earth (gleyed)	Peaty gley	Sphagnum (or flat or raised) bogs
Calcareous soil	Surface-water gley		Unflushed blanket bog
Rankers and skeletal soils	Ground-water gley		Eroded bog
Littoral soils			
Man-made soils			

In practice, C_{reg} values are not always available for all the combinations of species – soil types – rooting depths, due to the environmental conditions of the areas where the tree-pulling tests required for parameterisation of a new species were conducted. Additional fieldwork is normally required to obtain C_{reg} values for missing combinations, as for *E. globulus* (discussed in Chapter 3). However, values of C_{reg} of similar species are often used for the missing combinations of soil types and rooting depth, these similarities being in wood properties, canopy dimensions and foliar density, and root system architecture, as in the case of *Pinus pinaster (Ait.)* and *Pinus silvestris (L.)* (Gardiner et al., 2000). Occasionally, when C_{reg} values for a species are only available for certain soil type / rooting depth combinations, the missing values of interest for such species have been calculated by multiplying one of its known C_{reg} values by a ratio calculated between C_{reg} values of a species with a complete set of combinations, such as Sitka Spruce. This approach stems from the assumption that the proportionality of the resistance to overturning across combinations of soil type / rooting depth is the same for different species.

The critical turning moments for stem breakage and overturning are calculated with the following formulas from Gardiner et al. (2000):

$$\boldsymbol{M_{crit\_over} = C_{reg} * W_{stem}} \quad \textbf{(2. 4)}$$

$$\boldsymbol{M_{crit\_break} = \frac{\pi}{32} * f_{knot} * MOR * diam^3} \quad \textbf{(2. 5)}$$

where *M* is the total overturning moment (including that provided by the stem mass and the overhanging tree canopy, in Nm), *diam* is the stem diameter (in m), W_{stem} is the weight of the tree stem (in kg), calculated from stem volume and green wood density. The critical overturning moment is calculated at the tree base (i.e. *diam* = $diam_0$), while for breakage the critical moment is calculated at 1.3m (*diam* = dbh) or at the tree base (Hale et al., 2015). The critical breaking moment only needs to be calculated at breast height because of the assumptions that the stress on the outer fibres of the stem is constant along the height of the tree (Gardiner et al., 2000). The remaining parameters are species-specific: C_{reg} (N m kg^{-1}) is described above; *MOR* is the Modulus of Rupture (Pa) of green wood, derived from destructive bending tests, and f_{knot} is a dimensionless multiplier to account for the presence of knots that decrease wood strength (Lavers, 1969), whose values usually range between 0.8 and 1 (Ruel et al., 2010).

2.1.2 Calculation of Critical Wind Speeds

The model translates the moments calculated in Equations (4) and (5) into Critical Wind Speed (CWS) by means of canopy resistance, or drag, to wind flow, calculated with wind speed and aerodynamic roughness of the canopy itself (Gardiner et al., 2000). The canopy roughness is dependent on the canopy cover and crown size of the trees, which in turn can be derived from height and diameter of the trees with species-specific regression equations (Gardiner et al., 2008). The drag exerted by the crown has been also found to have a very high positive correlation with the mass of the branches (Gardiner et al., 2008). Usefully, these and other data on tree morphology and physical characteristics can be acquired directly from field measurements or derived from existing or user-defined yield models.

The method of Raupach (1994) is used in the model to calculate the aerodynamic parameters z_0 and *d* used in equations (2.1), (2.2), and (2.3):

$$\boldsymbol{d} = \left(\mathbf{1} - \left(\frac{\mathbf{1} - exp\left(-\sqrt{\boldsymbol{cd_1} * \boldsymbol{\Lambda}}\right)}{\sqrt{\boldsymbol{cd_1} * \boldsymbol{\Lambda}}}\right)\right) \quad \textbf{(2. 6)}$$

$$\boldsymbol{z_0} = \left(\boldsymbol{h} - \boldsymbol{d}\right) * \boldsymbol{exp}\left(-\boldsymbol{k} * \boldsymbol{\gamma} + \boldsymbol{\Psi_h}\right) \quad \textbf{(2. 7)}$$

$$\boldsymbol{\Lambda} = \mathbf{2}\left(\frac{\boldsymbol{canopybreadth}}{\mathbf{2}} * \boldsymbol{canopydepth} * {}^{\boldsymbol{C_D}}\!/_{\boldsymbol{D^2}}\right) \quad \textbf{(2. 8)}$$

$$\boldsymbol{\gamma} = \frac{\mathbf{1}}{\left(C_S + C_R * \frac{\boldsymbol{\Lambda}}{\mathbf{2}}\right)^{1/2}}, \boldsymbol{max\Lambda} = \mathbf{0.6} \quad \textbf{(2. 9)}$$

$$\Psi_h = \ln C_W - 1 + \frac{1}{C_W} \quad \textbf{(2. 10)}$$

where cd_1 (7.5), C_S (0.003), C_R (0.3), and C_W (2) are dimensionless constants, *canopybreadth* is the maximum width of the canopy (m), and *canopydepth* is the length of the live crown (m). The maximum width of the canopy is halved because the canopy is assumed to have a rhomboidal shape with *canopybreadth* as the value of the horizontal diagonal. The drag coefficient C_D (m s^{-1}) is a function of the wind speed of interest and is obtained from species-specific experimental data, as in Mayhead (1973), Rudnicki et al. (2004), and Vollsinger et al. (2005), with the following formula:

$$C_D = C * u^{-n} \quad \textbf{(2. 11)}$$

where *C* is the value of C_D at wind speed=0, and *n* is the exponent that best describes the power fit to the data.

By equating equations (2.4) and (2.5) with equation (2.3) and solving for wind speed, it is possible to calculate the critical wind speeds (for overturning: CWS_O; for breakage: CWS_B) that are able to generate the critical overturning and breaking moments:

$$CWS_O = \frac{1}{kD}\left[\frac{C_{reg} * SW}{\rho G d}\right]^{\frac{1}{2}}\left[\frac{1}{f_{CW}}\right]^{\frac{1}{2}} \ln\left(\frac{h-d}{z_0}\right) \quad \textbf{(2. 12)}$$

$$CWS_B = \frac{1}{kD}\left[\frac{\pi * MOR * dbh^3}{32\rho G(d-1.3)}\right]^{\frac{1}{2}}\left[\frac{f_{knot}}{f_{CW}}\right]^{\frac{1}{2}} \ln\left(\frac{h-d}{z_0}\right) \quad \textbf{(2. 13)}$$

Because the drag coefficient is a function of wind speed, and it is one of the terms of Raupach's formulas (1994) to calculate both aerodynamic canopy roughness and zero-plane displacement, equations (2.12) and (2.13) need to be solved iteratively (Gardiner et al., 2000). The iterative process that compares the turning moment exerted by wind with the critical bending moment of the tree begins with a nominal wind speed of 64 m s^{-1} (Gardiner and Quine, 2000) and terminates when the difference between the two is smaller than a precision factor, normally set at 0.01 m s^{-1}.

2.1.3 Estimation of the probabilities of exceeding the critical wind speeds

Lastly, the probability of winds exceeding the CWS requires knowledge of the average windiness of the site. In ForestGALES this can either be done by converting DAMS scores for the site of interest to the scale and shape parameters of a Weibull distribution, or by directly applying a Weibull distribution to high resolution local weather forecast data, in order to estimate the probability of CWS being exceeded. In both cases, the values of the critical wind speeds need to be converted to the corresponding speeds at 10m above zero-plane displacement, as per the standard form of meteorological data, on the basis of the logarithmic profile of wind speeds above the canopy top (Hale et al., 2015):

$$\boldsymbol{CWS_{10+d} = CWS * \frac{\ln\left(\frac{10}{z_0}\right)}{\ln\left(\frac{h-d}{z_0}\right)}} \quad \textbf{(2. 14)}$$

Weibull distributions have now been used for decades to describe distributions of wind speed and directions (Justus et al., 1978), and have been recently reviewed as remaining the most reliable and effective methods for such purposes (Seguro and Lambert, 2000). In addition to this, Weibull distributions allow for values obtained at anemometer's altitude to be effectively extrapolated at other altitudes (Justus et al., 1978). Because of the extreme sensitivity of the Weibull distribution, small changes in CWS result in large differences in the probability of extreme events (Gardiner et al., 2008). DAMS scores are created from British Ordnance Survey data on exposure, elevation, valleys shape and direction (Quine and White, 1993) which are related to the rate of tatter of tatter flags to estimate the windiness of the site. For instance, a DAMS score of 10 represents very sheltered conditions, a score of 17 is considered as quite exposed (Mason, 2003), and a score of 20 represents the limit for commercial forestry (Quine, 2000). DAMS scores can be presented in raster GIS (Bell et al., 1995), but no information on wind direction is included (Suarez et al., 1999). Alternatively, information on the windiness of a site of interest can be obtained from weather stations within reasonable distance to the forest stand (typically less than 50m, according to the resolution of the wind data), and the Weibull parameters values can be used in an airflow model such as WAsP (Wind Atlas Analysis and Application Program, Riso National Laboratory, Roskilde, Denmark) to produce estimates for the forest. Once the probability of wind damage for a site has been determined, return periods of extreme events can be calculated if data on the frequency of such events are available. Therefore the model can help identifying a point

in time when forest management procedures such as thinning should be performed, e.g. for the good of the forest or to maximise financial gain (Gardiner and Quine, 2000). More specifically, the model has identified that as trees grow older and taller the return periods decrease (Gardiner et al., 2008).

2.1.4 Use of the variable "gap size" in ForestGALES

As described in the Introduction, ForestGALES was developed to calculate the risk of wind damage for the interior of forest stands. In the code of the model, this is done by fixing the distance from the edge of the stand to a number of tree heights (e.g., 10). This then modifies accordingly the calculations of the wind profile over the canopy. This procedure is equivalent to calculating the risk for trees at the edge of a stand when the edge is a "green" edge, i.e. it has been in place since the establishment of the stand, thus allowing the trees to grow acclimated to the wind. That is, ForestGALES does not differentiate between trees at a distance from the edge equal to 10 times mean tree height, and trees at the edge of a stand that have been exposed to the wind profile typical of forest edges for the entire length of the rotation. This setting can be modified by imposing that the distance of the mean tree from the edge of the stand is equal to zero, therefore mimicking the effect of a "brown" edge, i.e. the forest edge adjacent to a recently created gap. Under this setting, ForestGALES calculates the risk of wind damage for trees that have been recently exposed to a gap, and therefore are not acclimated to the wind profile at the edge of the stand (e.g. Somerville, 1989). In real forests and plantations, both brown and green edges exist, and it is therefore of interest to evaluate the risk of wind damage in both situations. The ForestGALES simulations used for the studies in Chapters 3 and 4 assume a brown edge, while those in Chapter 5 assume a green edge. The choice of performing sensitivity analysis on the same species (*E. globulus*) for both a green and a brown edge allows investigating the behaviour of the model, and its sensitivity to its input variables, under two contrasting situations that are known to significantly affect the risk of wind damage. This is of particular interest for practical applications of ForestGALES.

2.1.5 Limitations of ForestGALES

Besides being based on a set of assumptions, every model has its limitations, and ForestGALES is no exception. In this section I briefly discuss the model's limitations with bullet-points, differentiating between limitations due to model structure, those due to data availability, and lastly those related to model validation and testing. Obviously, it can be argued that all issues are ultimately related to data availability, since the structure of a model is often dictated by the data available at the time of its design, and model validation requires validation data in addition to data used for model parameterisation.

Issues related to model structure:

- The model makes predictions of wind damage to monospecific virtual stands composed of trees all equal to the mean tree, which in most cases is only an approximation of the composition of a real stand. Recently, Hale et al. (2015) described a novel approach to the calculation of the critical wind speeds for breakage and uprooting that works at the level of the individual tree, thus allowing for variation within a stand.
- The model outputs are binary. That is, ForestGALES is not able to calculate probabilities of different levels of damage, but rather provides the user with either no damage to the stand, or total damage. This is due to a number of reasons, some related to data availability issues, and others to model structure.
- The model is quasi-static, in that it is not able to model the propagating wind loading on downwind trees that is experienced after upwind trees fail under the wind action. Byrne and Mitchell (2013) have attempted to solve this issue by coupling a modified version of the model, called ForestGALES_BC (Byrne, 2005) with the ArcView extension WINDFIRM. By running the coupled model iteratively it is possible to mimic the changes in the overall canopy structure of a stand exposed to a storm as the trees progressively fail under the changing wind loading (Gardiner et al., 2008).
- As shown by partial model validations in Great Britain (Gardiner et al., 2008; Suarez et al., 2002), together with reports from British foresters, model predictions are over pessimistic, i.e. the model predicts more damage than observed (Hale et al., 2015). This is a result of the modellers' preference for high accuracy of model outputs rather than low bias towards any of the binary outputs. This preference has recently been reversed in a novel method for calculating CWS that does not require

calculation of the Gust Factor (the “turning moment coefficient” method, described in Hale et al. (2015)).

Issues related to data availability:

- Apart from *E. globulus*, ForestGALES has only been parameterised for conifer species and its application is therefore restricted to those. More specifically, the largest amount of data used for model building is for spruce and pine species. This restricts the application of the model to broadleaf species, especially when not in leaf, i.e. in the winter season when damaging storms are most frequent.
- As mentioned in section 2.1.1, values of regression coefficients of uprooting moment against stem weight (C_{reg}) are not available for all combinations of rooting depth and soil type. Obviously, neither the values directly borrowed from similar species, nor those calculated with the known C_{reg} ratios of other species, have been experimentally tested. However, the model is built to issue a warning when simulations are launched for combinations of soil type and rooting depth whose C_{reg} values were not obtained with field experiments.
- The calculations of gap, edge, and gust factors, experimentally derived, are based on very small datasets. Hence, the uncertainty associated with these is potentially large.
- The nature of gustiness associated with very strong, heavily damaging windstorms is different from that of the wind speeds used in the experiments used to derive the Gust Factor (Dupont et al., 2015). This would suggest that the gustiness modelled with ForestGALES might not be appropriate for the calculations of the mean and maximum bending moments acting on the trees.
- The taper functions used in the calculations of tree stem mass and branch width are based on a generic tapered column shape rather than on species-specific taper equations. As a consequence, stem weight (used in the calculation of the overturning moments), stem mass (used in the calculation of the wind speeds responsible for stem breakage and overturning), and canopy weight (used in the calculation of the additional turning moment provided by the canopy), might be over- or under-estimated.
- With regards to the calculated outputs of the model, the confidence range of the application of ForestGALES is restricted to the range of tree dimensions (i.e., height

and dbh) of the experimental trees tested during tree-pulling. Very short trees (height < 5m) are typically excluded from tree-pulling experiments, due to the flexibility of their stem. In fact, very small trees are normally pulled vertically to measure their resistance to uprooting (e.g. Mokotedi et al., 2010). Some of the results presented in Chapter 3 are for very small trees, for comparison of the computed critical wind speeds and probabilities of damage with the results of Chen (2003). The need to approach these results cautiously is discussed in Chapter 3.

Issues related to the testing of model performance:

- The validation of wind risk models such as ForestGALES is difficult because of the relative infrequency of severe, damaging windstorms. Moreover, model validation requires knowledge of the variables required for the simulations, such as stand and tree characteristics, and accurate values of the wind speeds experienced during the event (Hale et al., 2015).
- Comprehensive uncertainty and sensitivity analyses of ForestGALES have never been performed. As a result, the reliability of the model's outputs is not known, nor is the relative importance of the model's input variables in driving variation in the outputs. This topic is further expanded in section 2.3 and is the subject of Chapter 3, partially, and of Chapter 5.

2.2 Fieldwork required for parameterising ForestGALES for new species

The fieldwork site for the parameterisation data of ForestGALES for *E. globulus* is described in Chapter 3, including maps and pictures of the site. In this section, the general procedures for the parameterisation of the model are discussed.

Parameterisation of ForestGALES for new species requires experimental work to gather species-specific data on tree characteristics for the calculations of wood density, canopy density, Modulus of Rupture, Modulus of Elasticity, and C_{reg} values. Allometric equations for canopy dimensions (width and depth), and for conversion from height of the tallest trees in the stand to the average tree height, are obtained from field measurements and calculated with linear regressions. Canopy breadth is normally regressed against dbh, and canopy depth

against mean tree height. Similarly, the values of C_{reg} for the model calculations of the overturning moment are obtained from linear regressions of total overturning moments measured in the field against the weight of the stem. The latter is calculated from wood density and stem volume, under the assumption that stem form is akin to a tapered column.

The fieldwork required for a novel species is carried out with tree-pulling experiments, with the method described in Nicoll et al. (2006). The first published account of tree-pulling is in Fraser and Gardiner (1967), who described the resisting force exerted by a tree's root-soil plate to uprooting as the maximum (critical) resistive turning moment measured at the base of the stem. The authors found the best correlation of this moment, which they termed "tree anchorage", to be with stem mass. Recently, Meunier et al. (2002) have confirmed stem mass to be the aboveground tree characteristic that best correlates with the critical turning moment, using linear regressions techniques. A major advantage of this is the possibility for effective comparisons of tree anchorage between different species, soil types, and rooting depths. The main assumption of tree-pulling is that static pulling tests are a reliable proxy of the dynamic sway of trees subject to wind. While the study of the mechanical response of trees under dynamic loads is a very lively area of research (e.g. James et al. 2006, Sellier and Fourcaud, 2009), the transition of findings of dynamic approaches to a practical applicability to the modelling of wind damage risk is still minor.

2.2.1 Tree selection

The minimum number of test trees is usually considered to be 24, equally divided in three dominance classes in regards to dbh: Sub-dominant, Co-dominant, and Dominant (Nicoll et al., 2006). The rationale for this subdivision is dictated by the statistical requirement to have a sufficient number of data points in three separate clusters for the regression of total overturning moments against stem weight to be significant. The minimum number of test trees is suggested on the basis that a number of trees will suffer stem breakage rather than overturning (~8.4% in Nicoll et al. (2006)), and therefore cannot be used to perform these regressions. The tree selection process begins by cataloguing all the trees in the selected area on the basis of their dbh. These are then ordered by increasing dbh and divided in the three dominance classes according to the quartiles of their distribution. Normally, the smallest

trees in the first quartile are excluded, and only the remaining three quartiles are associated with dominance classes, as shown in Table 2.3.

Table 2.3 - Subdivision of test trees in dominance classes after the quartiles of the distribution of their dbh.

Dominance Classes	
Sub-Dominant:	1st Quartile – Median
Co-Dominant:	Median - 3rd Quartile
Dominant:	3rd Quartile – Maximum

A random number is then assigned to each remaining tree and 24 test trees are randomly selected. In practice, however, feasibility and safety constraints often exist for certain trees, dictated by the tree-pulling operations described in section 2.2.2 below. As a result, some randomly selected trees might be removed from the experiment and substituted with others of the same dominance class that are more practical to test. Similarly, trees with obvious structural defects or showing evidence of disease are excluded from the experiments.

2.2.2 Experimental set-up

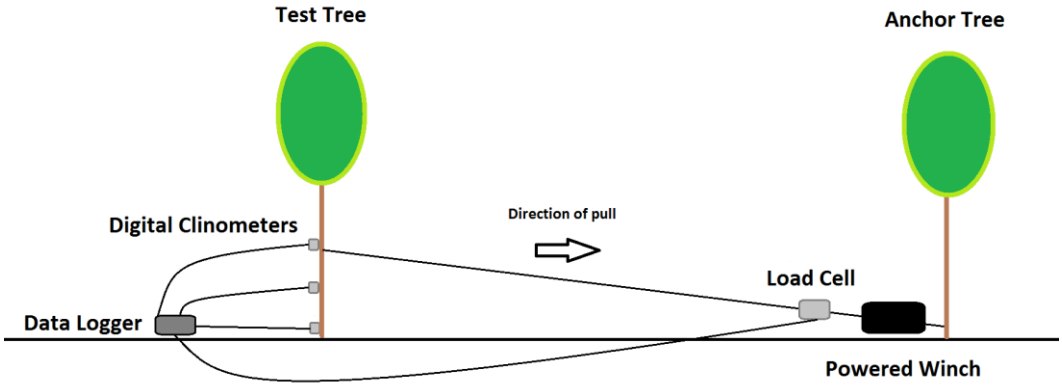
For each test tree, a corresponding anchor tree is selected amongst large trees excluded from the tests (dbh between the 3rd Quartile and the Maximum) located at a safe distance (i.e. more than twice the test tree height) from the test tree. All non-experimental trees between the test and anchor are felled, together with any adjacent ones whose canopy might interlock with the test tree's as the latter is being pulled, to avoid any interference in the experiment that might give a false force reading. A powered winch is attached at the base of the anchor tree with polyester webbing round-strops of safe working load appropriate for the size and characteristics of the test trees and the experimental site. For instance, when testing a species known for its strong rooting or dense wood (e.g. *E. globulus*), or in the case of a site with a well-drained soil, strops with safe working loads in the region of 10t are recommended. A load cell with a similarly appropriate capacity is attached to the winch, and a polypropylene woven rope (or equivalent metal cable) is extended from the load cell to the test tree, where it is attached with a strop of similar safe load to that used for securing the winch to the anchor tree. The rope attachment height is variable, but needs to be chosen to ensure that trees can be uprooted rather than their stem broken, for the calculation of C_{reg}

values. A general rule of thumb is to attach the rope between one third and half tree height (Cucchi et al., 2004; Nicoll et al., 2006). The capacity of the load cell must also be taken into account when choosing the attachment height, since the angle between the terrain and the pulling rope affects the force exerted on the tree, because of the principle of levers: *ceteris paribus*, lower attachment heights require stronger applied forces to uproot a tree. Exceeding the load cell capacity might result in damage to the equipment as well as artificially lower force readings. Three digital inclinometers are attached to the opposite side of the test tree's stem: one at the base, one at pulling height, and one halfway between the two. Attaching the inclinometers to the side opposite to the pulling directions minimises the risk of damage to the equipment as the tree falls to the ground under its own weight once it has failed. Figure 2.2 shows one of the test trees after pulling.

Figure 2.2 - Medium-sized Eucalyptus globulus (Labill.) tree after tree failure by uprooting. The inclinometers and the load cell are visible. On this tree, 2 sets of 3 inclinometers were used to minimise the risk of data loss due to equipment damage.

The inclinometers' purpose is to measure the stem angle from the vertical at tree failure, in order to calculate the height of the attachment point at maximum force, i.e. at tree failure, as the tree stem bends under the static pulling force. Using three inclinometers ensures that the bending of particularly flexible stems, as in young trees, can be accurately modelled if required. For the purpose of calculating the bending moment acting on the tree, however, only the top inclinometer (corresponding to the pulling height) is used. In fact, although the bending of a tapered beam, such as a tree stem, increases with the length of the beam (i.e. with tree height), and hence can affect the calculation of the bending moment, Nicoll et al. (2006) found that a 20% variation of the stem angle propagated through the model to produce only a 2% difference in the calculated critical wind speed for uprooting. Therefore, approximation of the region of the stem between the base and the attachment point to a rigid cantilever is accepted. Similarly, in the case of an approximately flat terrain, the effect of the terrain inclination between the base of the anchor and test tree is of little significance. The load cell and the inclinometers are connected to a data logger, positioned behind the test tree to avoid damage, to record data at short time intervals (usually 1 second). In some cases, the location of the test tree relative to a suitable anchor tree does not allow for a straight line between the trees of a length greater than the minimum safe distance. In these cases, an intermediate tree excluded from the test group, preferably of dbh comprised between the 3rd Quartile and the Maximum, and at a distance larger than test tree height from the test tree, is selected to act as a pivot. The anchor tree is selected at a position relative to the pivot tree so that the three trees can be visually connected with a broken line shaped as the letter "L". A strop -or a pulley- is attached to the pivot tree to allow for the winch cable to safely connect the winch to the test tree. A system of pulleys might also be used to increase the pulling force in case of exceptionally large trees or when the capacity of the available load cell is thought to be inadequate. Figure 2.3 shows the optimal experimental set-up and the pivot set-up.

a) Optimal setup



b) Setup with a Pivot Tree

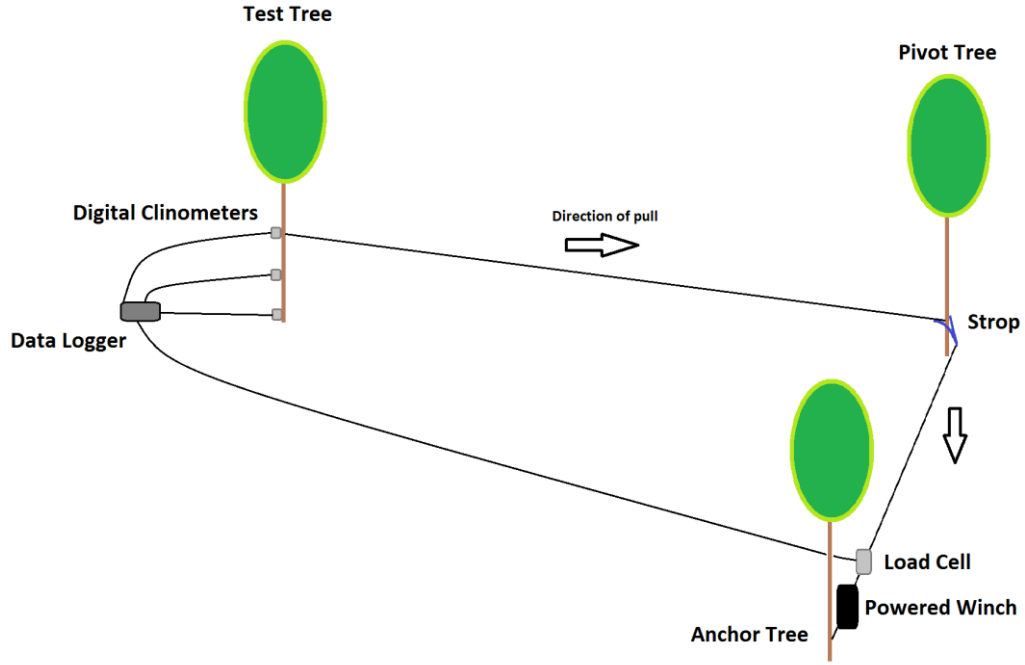


Figure 2.3 - Schematics of Tree-Pulling setup.

2.2.3 Data collection

Before each test, crown lateral dimensions are estimated in the four cardinal directions by visually estimating from ground level the extension of the crown in each direction, and measuring the projected distance between tree base and crown. This is used for the calculations of the canopy's cross-sectional area exposed to wind loading, and of the canopy

density. The horizontal distance between the test and anchor trees is measured for the calculations of the turning moment. Similarly, the attachment heights of the pull cable and the inclinometers are recorded for the trigonometric calculations required to calculate the turning moment, as described in section 2.2.5. An optical clinometer can also be used for the measurement of the angle of the pull cable to ensure the trigonometric calculations of the angle of pull are reliable. When tree-pulling is performed on a slope, the angle of the terrain must be estimated with an optical clinometer to adjust for the pull cable attachment height relative to the anchor tree base, again for the calculation of the turning moment (section 2.2.5). The cardinal direction of pull is recorded, as it can help in the interpretation of the test results in regards to the prevailing wind direction. After each test, tree height is measured. In addition, height of lowest live whorl, height of first live branch, and merchantable height at diameter = 7cm are recorded to aid in the modelling of crown dimensions. Stem diameter is measured in two perpendicular directions at 1m intervals, from the stem base to a stem height where stem diameter falls below 5cm, to accurately calculate stem volume in the form of a tapered column. All the branches are removed from the central stem, together with the canopy and stem above a diameter of 5 cm, and their weight in kg recorded to the first decimal place to provide the weight of the canopy for canopy density calculations. A stem section of one or two meters, depending on the size of the tree, is cut at 1/3 tree height and weighed to calculate green wood density for stem weight calculations. I refer to these stem sections as “density logs”. Whilst to ensure the highest accuracy of the value of stem weight the whole stem should ideally be weighed, this is considered to be too time consuming when in the field. To obviate this impediment, the choice of sampling for wood density at this height is dictated by the position of the centre of mass of a tree, as calculated for Sitka Spruce by Gardiner (1989), who also showed that the density of green wood increases with increasing tree height. Nicoll et al. (2006) reviewed and confirmed these findings, considering the calculation of density of green wood at the centre of mass of the stem to be a good approximation of the whole tree. These logs are collected for tests of wood mechanical properties, as described in the next section. For trees that fail by overturning, root plate’s width, height (top to hinge point), and hinge length (stem centre to hinge point) are recorded to the nearest cm. Similarly, three measurements of root depth are taken, at each of the 2 lateral extremities of the exposed root plate, and close to the tree base. These quantitative measurements of roots and root plate are often helpful in assigning the test trees to the correct soil type / rooting depth combination used for the calculation of C_{reg} values, which

can be a qualitative exercise. Maximum rooting depth is often difficult to establish, especially for species that grow a tap root (e.g. *P.pinaster* and *E. globulus*), but it is normally measured as the distance between the tree base and the furthest coarse root (diameter > 0.5 cm) that becomes exposed. The presence of root rot must be recorded as it can weaken the root system (Bergeron et al., 2009). Pictures of the root-soil plate should be taken from all directions for future reference. In the case of stem breakage, stem height and diameter at the rupture point are recorded, and pictures taken, again for further reference. When resources are available, roots that have remained in the soil, as well as tree stumps in the case of stem breakage, can be extracted for more accurate measurements of root size and depth.

2.2.4 Measurements of wood mechanical properties

At the end of the pulling experiments, the collected logs used for the calculation of green wood density need to be conditioned to 12% moisture content (MC) in a thermal test chamber. From each log, a flitch is cut from north to south, from which wood samples (as many as possible, to provide replicates) are extracted to be destructively tested for Modulus of Elasticity (MOE) and Modulus of Rupture (MOR). The dimensions of the flitches depend on the specific machinery used for the MOE and MOR tests. Tests are routinely performed with a bench-top tester, and values of MOE and MOR and post-test weight are recorded. After the tests, the samples are brought to a constant weight in an oven. Once the samples have reached a constant weight, their weight is again recorded and used to calculate the samples' MC at the time of the bending tests, with the following formula:

$$\boldsymbol{MC\%_{test}} = \frac{\boldsymbol{Weight_{after\ test} - Weight_{dried}}}{\boldsymbol{Weight_{dried}}} * \boldsymbol{100} \quad \textbf{(2. 15)}$$

This value can then be used to calculate the MOE and MOR of green wood of the tested trees. MOE is typically calculated with the method of Unterwieser and Schickhofer (2011):

$$\boldsymbol{MOE_{green\ wood}} = \frac{\boldsymbol{MOE_{MC\%test}}}{\boldsymbol{1 - 0.00825 * (MC\%_{test} - FSP)}} \quad \textbf{(2. 16)}$$

where FSP stands for "Fibre Saturation Point" and corresponds to MC~28%. Past this value of MC, MOE and MOR remain fairly constant (Unterwieser and Schickhofer, 2011). MOR for green wood is calculated with a similar formula:

$$MOR_{green\ wood} = MOR_{MC\%_{test}} - (MOR_{MC\%_{test}} * \frac{FSP - MC\%_{test}}{100}) \quad \textbf{(2. 17)}$$

2.2.5 Data processing for model parameterisation

Field data gathered during the pulling tests must be processed to derive most species-specific parameters for the parameterisation of ForestGALES for a new species. These parameters model tree characteristics such as frontal canopy area, canopy volume, stem wood density, and stem volume. These are used to calculate the total turning moments generated by the applied pulling force and by the mass of the stem and of the canopy as the trees fail during the experiments. In addition to this, the parameters to model crown streamlining, fundamental to the calculation of the critical wind speeds, are required for any new species. Given the large resources necessary for the calculations of these parameters with wind tunnel tests, drag coefficients are often borrowed from other species, chosen because of the similarities of their canopy with that of the new species in terms of morphology and leaf area density. An example of this is briefly discussed in Chapter 3.

2.2.5.1 Tree dimensions

Density logs and tree stems are normally modelled to approximate tapered columns. For the stem, the two stem diameter measurements, taken at 1m intervals from the stem base until the tree height where the diameter falls below 5cm (THD5), are averaged and used in the calculations of logs and stem volumes. The calculation of the volume of density logs is trivial. Here, the formula to calculate the volume of the stem is shown:

$$\boldsymbol{Stem\ volume} = \sum_{h=1}^{h=(THD5)} \left[\frac{\pi}{3} * \left(\frac{diameter_{h-1}}{2}\right)^2 + \left(\frac{diameter_{h-1}}{2} \times \frac{diameter_h}{2}\right) + \left(\frac{diameter_h}{2}\right)\right] \quad \textbf{(2. 18)}$$

For each tree, wood density is calculated by dividing the measured weight of the density log by its volume. The values of wood density for all the tested trees are then averaged and used in the model. Alternatively, wood density data can be obtained from the literature. Stem weight, calculated by multiplying wood density by stem volume, is used in the linear regressions for the calculations of C_{reg}.

The frontal area of the canopy and its volume are calculated with the appropriate geometric formulas. For instance, the frontal area of the typical conifer tree is approximated to a

rhomboid shape, while the volume of the canopy of *E. globulus* trees is modelled as the sum of 2 half-ellipsoids, because the middle value of their canopy breadth rarely coincides with the position of the vertical axis of the stem. For each tree, live canopy depth is calculated by subtracting the height of the lowest live whorl from tree height. The horizontal distances between the tree base and the vertical projections of the canopy to the ground in the four cardinal directions are used to calculate canopy breadth. For each tree, the canopy weight measured in the field is divided by its modelled volume to calculate the density of the canopy, which is then averaged and used in the model's simulations.

2.2.5.2 Calculation of the critical bending moments

The schematics of the forces acting on the test trees and the relative angles are displayed in Figure 2.4, below. The pull exerted by the winch (F_{max}) during the pulling tests is the major force acting on the trees. The force (m) exerted by the mass of the stem and of the canopy adds to the vertical component of the force as the trees are pulled over. When a tree fails in correspondence to the maximum applied force, the angle (α) between the vertical and the test tree at F_{max} is calculated as the difference between the readings of the top inclinometer at the time of tree failure minus that when the test tree is at rest. The pulling angle θ can be derived trigonometrically from the distance between the test and anchor tree (d) minus the horizontal displacement of the test tree (x), and the winch cable attachment height (L) that corresponds to the height of the top inclinometer. Measuring the angle of the pull cable with an optical clinometer can help validating the calculation of the angle θ.

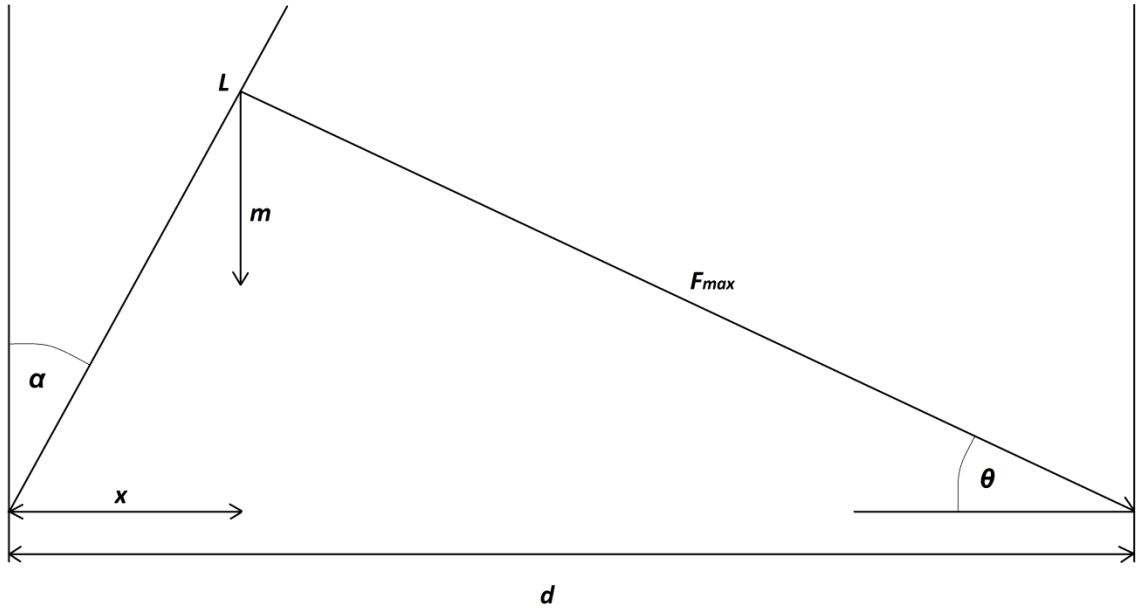


Figure 2.4 - Schematic representation of forces acting on a tree during tree-pulling experiments, and angles involved in the calculations of Total critical bending moment (adapted from Nicoll et al., 2006). F_{max}: applied force at time of tree failure; *d*: distance between test and anchor tree; *x*: horizontal displacement of test tree at tree failure; *m*: force provided by tree (stem and canopy) mass; α: angle between vertical and test tree at time of failure; ϑ: angle between horizontal and pull cable. *L*: attachment height.

The critical turning moment ($TM_{crit,applied}$ (N)) applied at stem base is calculated with the following formula:

$$TM_{crit,applied} = F_{max} * 9.81 * \cos\theta * L * \cos\alpha \quad \textbf{(2. 19)}$$

The centre of gravity of the stem is normally assumed to be located at ⅓ tree height and is a function of tree taper, while the centre of gravity of the canopy is assumed to be in the middle of the canopy. The additional loading provided by the masses of the stem and the canopy ($TM_{crit,tree\ components}$ (N)) is then calculated as follows:

$$TM_{crit,tree\ components} = 9.81 * \sin\alpha * \left[CrownWeight * \left(TreeHeight - \frac{CanopyDepth}{2}\right) + StemWeight * \frac{TreeHeight}{3}\right] \quad \textbf{(2. 20)}$$

Adding the two turning moments gives the Total critical bending moment ($Total_{TM}$ (N)). This is then used in linear regression models against stem weight to calculate C_{reg} values for the appropriate combinations of soil type and rooting depth. These regressions are forced through the origin because, as the weight of the tree approaches zero, so should $Total_{TM}$,

intuitively (Gardiner et al., 2000). Accuracy of model predictions of calculated maximum turning moment can be tested with linear regressions of $Total_{TM}$ against the best predictors identified by Gardiner et al. (1997) and Peltola et al. (2000) for uprooting (tree height*dbh^2) and stem breakage (dbh^3) using experimental data gathered during the tree-pulling experiments.

2.3 Sensitivity analysis of model predictions

2.3.1 Local sensitivity analysis of ForestGALES

A sensitivity analysis of the input variables and internal parameters of the GALES component of the model was performed by Gardiner et al. (2000). The authors used traditional (local) sensitivity analysis techniques whereby internal parameters and a small range of discrete values of the inputs were increased by $\pm$20%, with the exception of streamlining parameters that modify the sail area of a tree crown exposed to the wind (Mayhead, 1973), which were incrementally set at 20, 40, and 60%. Starting values of tree height and diameter were 20m and 20cm, respectively. The sensitivity analysis was performed for only one species, with Scots pine species-specific parameters. The results of the analysis showed (in decreasing order) the importance of dbh, tree height, and stem density with regards to the calculation of the overturning moment. These model inputs were important also in the calculation of the CWS for overturning, together with the Gust Factor, stand density, streamlining parameters, drag coefficient, and crown dimensions. For the bending moment, the most important variables were dbh, MOR, and tree height. For the calculation of the associated CWS, tree height became more important than MOR. In addition to these variables, the analysis showed that the model was sensitive to the Gust Factor, stand density, streamlining parameters and drag coefficient. Because the authors employed a local sensitivity analysis method, the effect or the significance of interactions between the inputs was not explored. As mentioned in Section 1.6 in the Introduction and discussed below, local sensitivity methods perform poorly with non-linear models (Saltelli et al., 2004) such as ForestGALES. For this reason, I employ global sensitivity analysis methods for the sensitivity analysis of ForestGALES. The remaining of Section 2.3 provides an introduction to the theoretical background for the sensitivity analyses reported in Chapter 3 and in Chapter 5, where a comprehensive global sensitivity

analysis of ForestGALES is presented, and the specific methods adopted are discussed at length.

2.3.2 An introduction to the available sensitivity analysis methods

The use of models to understand and describe events has become prominent in every scientific discipline and has extended to many industry sectors (Saltelli et al., 2009). The task of modelling human-made and natural phenomena is often complex and requires a thorough understanding of the system being modelled. Especially in the case of models of natural phenomena, multiple descriptions of the processes involved, and the corresponding models that attempt to describe them, are often plausible (Cariboni et al., 2007; Gardiner et al., 2008). By identifying and mathematically describing the variables that influence a phenomenon, and their interplay, it is possible to model natural and human-induced phenomena in such a way that predictions of their future behaviours can be made (Saltelli et al., 2000). While the comprehensiveness and finesse of a model's structure are theoretically limited only by the current understanding of the phenomenon described, practicality demands that the smallest number of variables is used that can account for the largest variance in the model output (Campolongo and Saltelli, 1997). That is, a judgement has to be made, considering the requirements of a model's users and resources availability, about whether adding extra variables in a model will significantly improve its predictive ability. This is especially important when data gathering is difficult or uneconomical (Saltelli et al., 2008).

A few words about the nomenclature used throughout this section of my thesis are required. The letters "*X*" and "*Y*" generally refer to model inputs and outputs, respectively. When in capital case, they indicate a variable, e.g. tree height and probability of breakage. When in lowercase, they refer to a specific value of said variable. When in bold, they refer to a vector of (values of) inputs or outputs. For instance,

$$\boldsymbol{X} = \left(\boldsymbol{X_i}, \boldsymbol{X_j}, \dots, \boldsymbol{X_m}\right) = (\boldsymbol{tree\ height}, \boldsymbol{dbh}, \dots, \boldsymbol{DAMS}) \quad \textbf{(2. 21)}$$

$$\boldsymbol{Y} = (\boldsymbol{Y_a}, \boldsymbol{Y_b}, \boldsymbol{Y_c}, \boldsymbol{Y_d}) = \left(\boldsymbol{CWS_B}, \boldsymbol{CWS_O}, \boldsymbol{Probability\ of\ Breakage}, \boldsymbol{Probability\ of\ Overturning}\right) \quad \textbf{(2. 22)}$$

where *m* is the number of input variables.

Model input variables are characterised by an intrinsic uncertainty, due to limitations in carrying out their mensuration, or to the incomplete scientific knowledge of the same processes that are being modelled (Saltelli et al., 2000). A first step to ensure clarity and transparency of model outputs is to be able to quantify this uncertainty (Molinari, 2007). A straightforward way to quantify the uncertainty in the output as a result of the propagation of the uncertainty in the input variables is known as "uncertainty analysis", which requires the calculation of the expected value (i.e. the mean) and the variance of the output (Saltelli et al., 2000). When attempting to investigate how the uncertainties in the input variables influence the uncertainty in the output, it seems logical to proceed with a Monte Carlo analysis. Monte Carlo methods allow sampling from a multivariate joint distribution of the vector $\boldsymbol{X}$ of input variables to propagate the input's uncertainties through the model to the output, creating a probability distribution function (PDF) of the output Y (Saltelli et al, 2008). Knowing the PDF of the output allows for the calculation of statistical moments such as the mean, variance, and standard deviation of the output (Molinari, 2007). Sampling from the input variables' joint PDF is particularly important when two or more variables are correlated, while in the case of completely orthogonal (i.e. independent) variables, sampling from the marginal PDF of each variable is allowed and more economical, since it removes the need to calculate the joint PDF (Saltelli et al., 2008).

Having obtained information on the uncertainty of the outputs of the model, one might wish to delve further into the analysis of their model's behaviour in regards to the uncertainties associated with the model input variables. A powerful method to assess the contribution of each variable, and sometimes of their interplay, to the model output's variance is "sensitivity analysis". The purposes and the benefits of sensitivity analysis are many, as reported in Section 1.6. Various methods exist to perform such analysis (see Saltelli et al. 2000), and the interested reader is directed to the relevant references. For the scope of this thesis, a brief description of the most commonly adopted methods in the literature is given. Special emphasis on the methods used in Chapters 3 and 5 is given in the relevant methodology subsections of these Chapters.

2.3.3 Local methods for sensitivity analysis

As discussed in Section 1.6 of the Introduction, when applying local sensitivity analysis methods only one input variable at the time is allowed to vary within its range, while all the other variables are fixed to a nominal value within their range (Saltelli et al., 2006). Thus, only one point in the variables' space is explored while second and higher order interactions between variables are neglected (Saltelli et al., 2008). For an output Y, and a vector of *m* input variables ***X***, this means calculating $\left(\partial_y/\partial_{x_i}\right)_{x=x^*}$ for each $X_i \in \boldsymbol{X}$, *(i= 1…m)* when fixed on an arbitrary value *x** (usually the mean) of each X_i (Sobol', 2001). This is the most common form of sensitivity analysis used by modellers, but often inappropriate (Saltelli et al., 2008). On the other hand, while not all the methods to perform GSAs allow for the estimation of the interaction terms between input variables, GSAs do however consider the entire range of values of each variable. GSA methods estimate the effect of each variable on the model output's variance by taking into account the variability of all the other variables (Saltelli et al., 2004). Hence, the term "global" is appropriate.

2.3.4 Global methods for sensitivity analysis

The most common GSA methods include regression analyses, First-Order Reliability Methods (FORM), and variance-based methods (Saltelli et al., 2008). All of these have found successful applications in various scientific disciplines and have suitable applications as well as limitations (Saltelli et al., 2000). When confronted with a high number of input variables (e.g. $m \gg 50$), screening tests such as the one introduced by Morris can be useful to identify a subset of ***X*** on which to focus a GSA (Morris, 1991), so as to reduce the high computational requirements of GSA methods (see Sections 1.6.2 and 2.3.4). The number of input variables of ForestGALES is low (7, plus species acting as a trigger for species-specific formulas and values). Therefore, for the work in my thesis (Chapters 3 and 5) it was not necessary to perform a screening exercise. However, the reader interested in screening methods for GSA is directed to the relevant literature (e.g. Saltelli et al., 2000; Saltelli et al., 2008). The next sub-sections briefly describe regression analyses and FORM techniques, before introducing two powerful variance-based methods for sensitivity analysis, the Fourier Amplitude Sensitivity Test and the indices of Sobol'. The latter is used in the sensitivity analysis of ForestGALES and as such is explored in detail in Chapters 3 and 5.

2.3.4.1 Global methods: Regression analyses

Regression analyses, such as the computation of Standardised Regression Coefficients and their ranked equivalents, are global methods that are able to explore the entire range of each variable by "multi-dimensional averaging" when the sample size of $X_i \in \boldsymbol{X}$ is large (Saltelli et al., 2008). However, these methods are heavily reliant on assumptions of model's linearity and monotonicity (Campolongo and Saltelli, 1997). The associated coefficient of determination R_y^2 is nevertheless informative as a qualitative measure of the presence of interactions between input variables, as values smaller than 1 indicate the presence of interactions (Saltelli et al., 2008).

2.3.4.2 Global methods: First Order Reliability Methods

First Order Reliability Methods (FORM) are useful when the analysis does not focus on proportioning the output *Y*'s variance to the variance of the inputs ***X***, but rather on the probability that a critical value of *Y* is exceeded. In these applications, the sensitivity of the output to the input variables is calculated as the derivative of the minimum distance between a joint distribution of ***X*** and a "hypersurface" within the input space that separates the region of input space that produces an "acceptable" realisation in *Y* (e.g. below the critical values) from the region that exceeds the critical values of *Y* (Saltelli et al., 2000).

2.3.4.3 Global methods: Variance-based GSA

Recent developments in the field of sensitivity analysis have brought forward the concept of using variance as an indicator of the inputs' contribution to the model's outputs. The variance-based approach allows identifying the input variables that drive most of the variation in the output, and hence are most important, by relating the inputs' variance with the outputs' (Saltelli et al., 2000). Moreover, these "variance-based" GSA methods are "model-free" approaches, in the sense that they do not require any assumptions on the linearity, additivity, or monotonicity of the model, and can generally describe well interactions between variables (Saltelli et al., 2008). Variance-based GSA methods are similar to ANOVA techniques in that they share the same idea of decomposing the total output's variance, which has naturally a value of 1, into summands of conditional variances of

increasing dimensionality. In the following Section I provide an intuitive approach to the rationale for the use of conditional variances as sensitivity measures.

2.3.4.3.1 Why using conditional variances for sensitivity measures?

Sobol' (2001) showed that, provided that a function *f* is defined in an *m*-dimensional unit hypercube, and it is square-integrable (i.e. it has boundaries, because the integral of the square of the absolute value of *f* is finite), there exists an expansion of *f* such as:

$$\boldsymbol{f = f_0 + \sum_i f_i(X_i) + \sum_{i,j} f_{i,j}(X_i, X_j) + \cdots + f_{1,2,3,\ldots m}} \quad \textbf{(2. 23)}$$

This expansion, called "high-dimensional model representation" (HDMR), contains 2^m terms: one constant term (f_0), *m* terms are first-order functions, $\binom{m}{2}$ terms are second-order, and so on (Saltelli et al., 2008). When all the inputs are orthogonal (i.e. there are no correlations), the HDMR expansion is unique, and the terms in the expansion can be calculated with the conditional expectations of the output of *f* (Sobol', 2001):

$$\boldsymbol{f_0 = E(Y)} \quad \textbf{(2. 24)}$$

$$\boldsymbol{f_i(X_i) = E(Y|X_i) - f_0} \quad \textbf{(2. 25)}$$

$$\boldsymbol{f_{i,j} = E(Y|X_i, X_j) - f_i(X_i) - f_j(X_j) - f_0} \quad \textbf{(2. 26)}$$

where, adopting Bayesian notation, $E(Y)$ is the expectation of the output Y (i.e. its mean), $E(Y|X_i)$ is the expectation of Y conditional on the variable X_i, and $E(Y|X_i, X_j)$ is the expectation of Y conditional to the pair of variables X_i and X_j. Conditional expectations such as $E(Y|X_i)$ can be calculated empirically by slicing the domain of X_i and averaging the values of the conditional output $(Y|X_i)$ within each slice (Saltelli et al., 2008). With this approach, calculating the conditional variance $V[E(Y|X_i)]$ provides a measure to discriminate between influential and uninfluential variables. In fact, an influential variable will have a large conditional variance, while an uninfluential variable will conversely have a small variance. As is often the case, it is easier to intuitively grasp this concept with visual examples. Figure 2.5 shows scatterplots of two fictitious variables X_i and X_j, whereby X_i is influential and X_j is not. The dotted vertical lines indicate that the domains of X_i and X_j are sliced in order to calculate the conditional means (shown in the two graphs at the bottom).

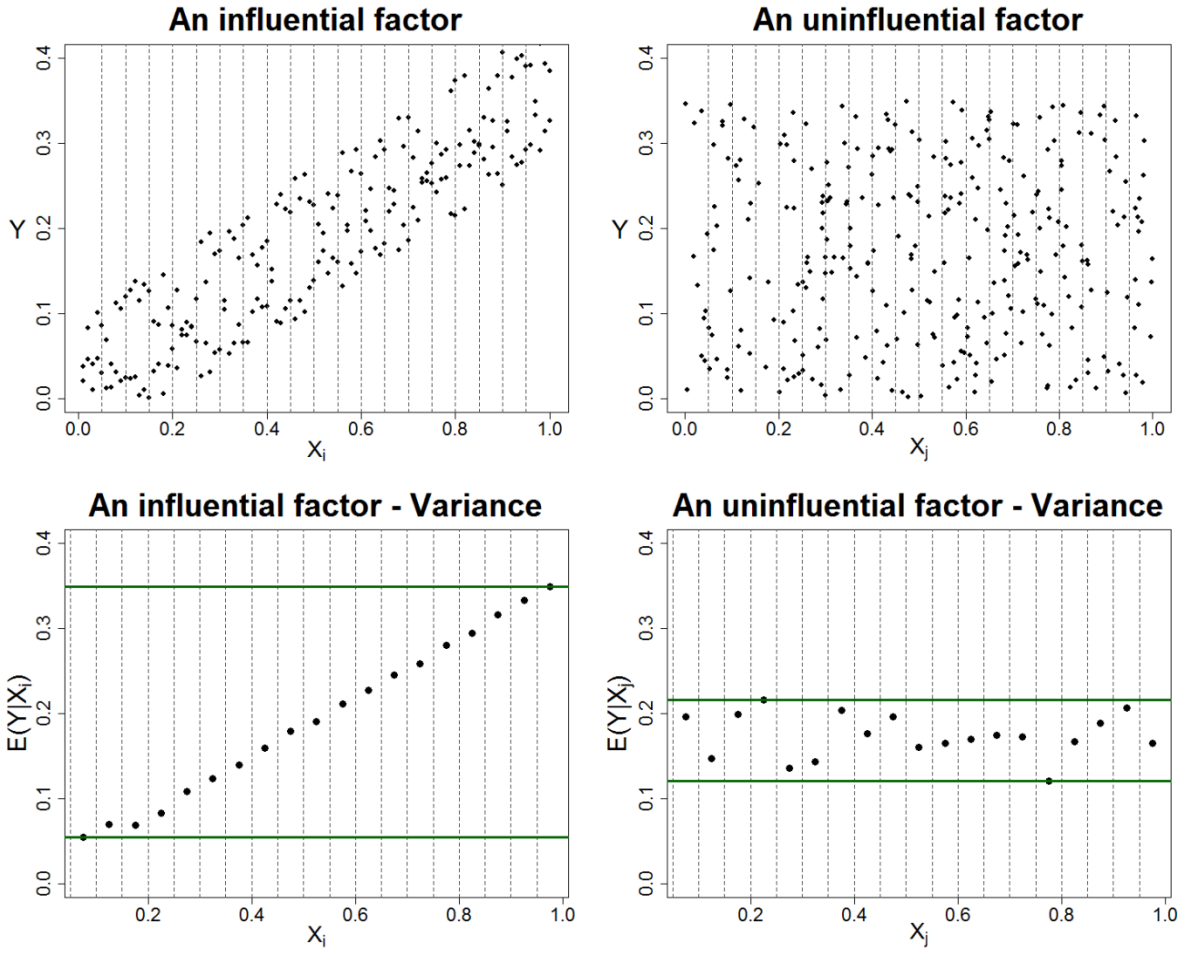


Figure 2.5 - Using conditional variances as measures of sensitivity of the output Y of a mathematical function or model.

As shown in the top-left scatterplot in Figure 2.5, a clear linear pattern between Y and X_i can be seen. Conversely, in the top-right scatterplot, no pattern can be identified between Y and X_j. This consideration alone is sufficient to show that, qualitatively, it is possible to differentiate between X_i and X_j in terms of their importance in driving variation in the output Y. By introducing the conditional expectations, and subsequently the conditional variances, it is possible to quantify the sensitivity of the output to the two inputs. The dots in the two scatterplots at the bottom of Figure 2.5 represent the conditional expectations calculated for each slice of the domains of the inputs. The green horizontal lines show the conditional variances of the output with regards the two inputs. Clearly, the influential variable X_i has a much larger conditional variance than the uninfluential X_j (ranges between the horizontal green lines are 0.31 and 0.08 respectively, in this example), providing an unambiguous quantitative method to calculate the sensitivity of the output Y to the two inputs. The FAST

and the Sobol' methods base their calculations of the sensitivity measures on the conditional variances.

2.3.4.3.2 Variance-based GSA methods: Fourier Amplitude Sensitivity Test and Indices of Sobol'

The two most powerful variance-based GSA methods are FAST, and the indices of Sobol'. A generalisation of the latter for correlated variables was adopted for my research, and as such the method of Sobol' is discussed in more detail in Chapters 3 and 5, where the method is adopted. The choice of the method of Sobol' was dictated by the fact that a generalisation of FAST for correlated variables does not exist at the moment. Moreover, the Sobol' method has a number of other advantages, briefly discussed in Section 2.3.4.3.3. The two methods and some considerations that pertain to variance-based GSA methods are presented below.

Cukier et al. (1973) and Cukier et al. (1978) were the first to propose the use of conditional variances for sensitivity analysis in their studies of complex chemical systems. Their method, known as FAST (Fourier Amplitude Sensitivity Test), is based on a Fourier decomposition of the model under scrutiny, and correlates the amplitude of the frequency w_i of each factor X_i, and its higher harmonics, with the sensitivity of the output Y to that factor. More specifically, if X_i has a strong influence on the output, this will oscillate greatly at the frequency w_i. Then, the spectra of the fundamental frequency w_i and its harmonics are calculated on Y to estimate the conditional variance of Y with regards to X_i (Saltelli et al., 1999). The original FAST method only allowed the calculation of the main sensitivity measures for a model's input variables, also known as "first-order" sensitivity indices (S_i). First order sensitivity indices are based on the conditional variance of the output with regards to the single inputs, and as such do not include any interactions effects. These indices have been used by other investigators, who often referred to them as "importance measures" (e.g. Iman and Hora, 1990; Homma and Saltelli, 1996; Sobol', 2001). When it was first developed, the FAST method received little attention due to the complex task of translating their algorithms into workable computer code. Other authors (Saltelli et al., 1999) have built upon the original FAST method to improve the original algorithms and to allow the calculation of the "total" sensitivity indices (S^T_i), which include the effect of interactions with other variables. An Extended-FAST method that can compute the variables' S^T_i was proposed by Saltelli et al. (1999) and its

performance was shown in some cases to be superior to the method of Sobol' in terms of computational cost.

The method of Sobol' is based on the propagation of the uncertainties in the inputs to the outputs. The uncertainty in the inputs is expressed via independent marginal distribution functions. This method is similar to ANOVA techniques, in that the total output's variance, which has naturally a value of 1, is decomposed into summands of increasing dimensionality, and follows from the formula decomposition expressed in Eq. 23 to 26. These summands are calculated from the main effects of each X_i, to second order interactions between X_i and X_j, and finally to higher-order interactions such as $X_i,X_j,\ldots X_m$ (Saltelli et al., 1999). In mathematical terms, and using the standard nomenclature of sensitivity analysis, this can be shown as:

$$\boldsymbol{V = \sum_{i=1}^{m} V_i + \sum_{i \le j \le m} V_{ij} + \cdots + V_{12\ldots m} = 1} \qquad \textbf{(2. 27)}$$

Where V is the total variance of the output, V_i is the variance due to first order terms of all the inputs X_i, and V_{ij} is the variance of second order interactions, for m input variables (Campolongo and Saltelli, 1997). First order sensitivity indices of the output Y to the inputs X_i can then be introduced, simply by normalizing the first order variances V_i by the total variance V (Sobol', 2001). This is commonly done using the variance of the expectation of Y conditional on a fixed value of X_i, by averaging for all values of X_i (Saltelli et al., 1999). This can be written as:

$$\boldsymbol{S_i = \frac{V(E(Y|X_i)}{V_Y}} \qquad \textbf{(2. 28)}$$

Where the S_i is the first order sensitivity index for X_i, the numerator is the conditional variance, and V_Y is the total variance of Y. This identity is one of the aforementioned sensitivity measures. When calculating the S_i numerically, the numerical estimation of the numerator term is normally done with Monte Carlo methods. This involves the use of two Monte Carlo matrices (e.g. A and B) of size N by m generated from the same joint-PDF of the input vector $\boldsymbol{X}$, plus m matrices C_i which are composed of all the columns of B except the i-th column, which is taken from A. The chosen number of model iterations is N, which normally ranges between a few hundred to several thousands, depending on the number of variables (Saltelli et al., 2008). For the calculation of S_i of each input variable X_i, the values of the matrices A and C_i differ for all the variables but X_i (it is said that X_i is not re-sampled) (Saltelli et al., 1993). The next step involves the multiplication of the corresponding values of $Y_{A,Ci}$ between the two matrices. Then, the total mean of Y is subtracted from this product and all

products are summated and averaged by N. It follows that, if variable X_i is influential, high values of X_i from one matrix will be multiplied by high values in the other, yielding high values of the conditional variance on X_i. The less influential X_i is, the lower these values (Archer et al., 1997).

With the method of Sobol', total sensitivity indices (S^T_i) can be computed by dividing the input vector $\boldsymbol{X}$ into two subsets (Campolongo and Saltelli, 1997). The procedure can be summarised as follows: the first subset of $\boldsymbol{X}$ only contains X_i, the second all the remaining variables (i.e. $\boldsymbol{X}_{-i}$), which are in this sense grouped together. Calculating the total variance V as previously shown (which has a value of 1), and similarly calculating $V_{\boldsymbol{X}_{-i}}$, it follows that:

$$\boldsymbol{S_i^T = 1 - V_{X_{-i}}} \qquad \textbf{(2. 29)}$$

By repeating for all X_i, it is possible to calculate the total effects of all the input variables. With the Monte Carlo approach, this is done as for the S_i, but using matrix B instead of A. Therefore, in terms of the cost of the analysis to calculate all the S_i and the S^T_i, $N + N$ model runs are required for the computation of matrices A and B, plus m times N for matrices C_i, for a total of $N(m + 2)$ model runs (Archer et al., 1997; Saltelli et al., 2009). Before the development of efficient algorithms for the numerical estimation of sensitivity indices for correlated variables, the issue of correlation was dealt with by grouping correlated variables in a way akin to the subset $\boldsymbol{X}_{-i}$ used for the calculation of the S^T_i. However, information on the single variables within a group is lost when variable-grouping is performed.

When a model is described with a large number of variables, or when two or more variables are non-orthogonal (i.e. correlated), it can be useful to form groups of variables describing them with a joint-PDF and treating these groups as single variables. It is therefore fortunate that variance-based methods are able to cope with groupings (Saltelli et al., 2008). However, when grouping is performed, information on the single variables, and on all the interactions in which they are involved outwith the rigid boundaries of their grouping, is lost. Therefore, when two or more variables that are expected to be influential to the output are strongly correlated, it is desirable to be able to treat them independently. For ForestGALES, this is the case for tree height and dbh, tree-characteristics which are strongly correlated in the natural world. Throughout the model, these two variables appear in a large number of formulas, in the calculations of canopy and stem dimensions (both variables), in the mechanical description of the trees under the wind loading (both), and in the calculations of the gustiness

of the wind used for the bending moments (tree height). In the last decade a number of approaches to deal with the issue of correlation have emerged which share the idea of decomposing the sensitivity indices for each variable into a correlated and an uncorrelated part. Xu and Gertner (2008) proposed to decompose the first-order sensitivity indices in two parts: one (S^u_i) that accounts for the uncorrelated contribution of X_i to the output's variance, and another (S^c_i) that describes the contribution of the correlations (e.g. $S_i = S^u_i + S^c_i$). This decomposition allows identifying the spurious variables that are influential only because of their strong correlation with influential ones. In fact, a variable with high S_i and low S^u_i owes its influence to the correlation with other significant variables. Mara and Tarantola (2012) propose an orthogonalisation of the correlated inputs, followed by the calculation of the sensitivity indices of the new orthogonal set of variables, which are finally decomposed into a correlated and an uncorrelated part. However, their ANOVA-HDMR decomposition is not unique and requires prior assumptions on the relative influence of the variables. Most (2012) and Kucherenko et al. (2012) propose similar decompositions of the variance of the output and have different advantages, especially with regards to the efficiency of the sample generation and the transformations of the variables set for the calculation of the sensitivity indices. These transformations model the dependence structure of a variable set by a normal copula parameterised with its own correlation matrix (Kucherenko et al., 2012). This approach is based on Sklar's Theorem (Sklar, 1973), which allows to decompose a set of correlated variables described by their multivariate joint distribution into a set of univariate marginal distribution functions and a copula to describe the dependence structure of the original set. This approach is particularly convenient for variance-based GSA, which characterise the model's input variables in terms of their PDFs. More details about the copulas approach are given in Chapter 5.

2.3.4.3.3 Quasi-Monte Carlo "random" numbers

One of the main differences between the method of Sobol' and FAST (both classical and Extended) is related to the sampling of the input space from the input's PDFs when producing "random" sequences of input for uncertainty and sensitivity analyses. In particular, the method of Sobol' is more efficient when the distributions of the input variables are poorly known (Saltelli et al., 2008; Saltelli et al., 2009). FAST methods use a search curve, continuous in the space of the inputs, to create the input sample to perform uncertainty and sensitivity

analyses (Saltelli et al., 2000). Because of the well-known misbehaviour of Fourier series in the presence of discontinuities (Hewitt & Hewitt, 1979), when the behaviour of the model cannot be predicted (i.e. at the exploratory stages of the analyses), the method of Sobol' should be favoured over FAST. The method of Sobol' is also more powerful when the differences between the influences of each variable on the total output variance are small (Saltelli et al., 1999). This method is based on sequences of quasi-random numbers, often called LP_{τ} or Sobol' sequences, which have been shown to converge to the estimation of the total variance more rapidly than classic Monte Carlo methods (Sobol', 1990; Kucherenko et al., 2012). These methods are called "quasi-Monte Carlo" methods (Sobol', 1998). Quasi-Monte Carlo methods have been demonstrated to outperform Monte Carlo methods especially in problems of variance reduction (Sobol', 2001).

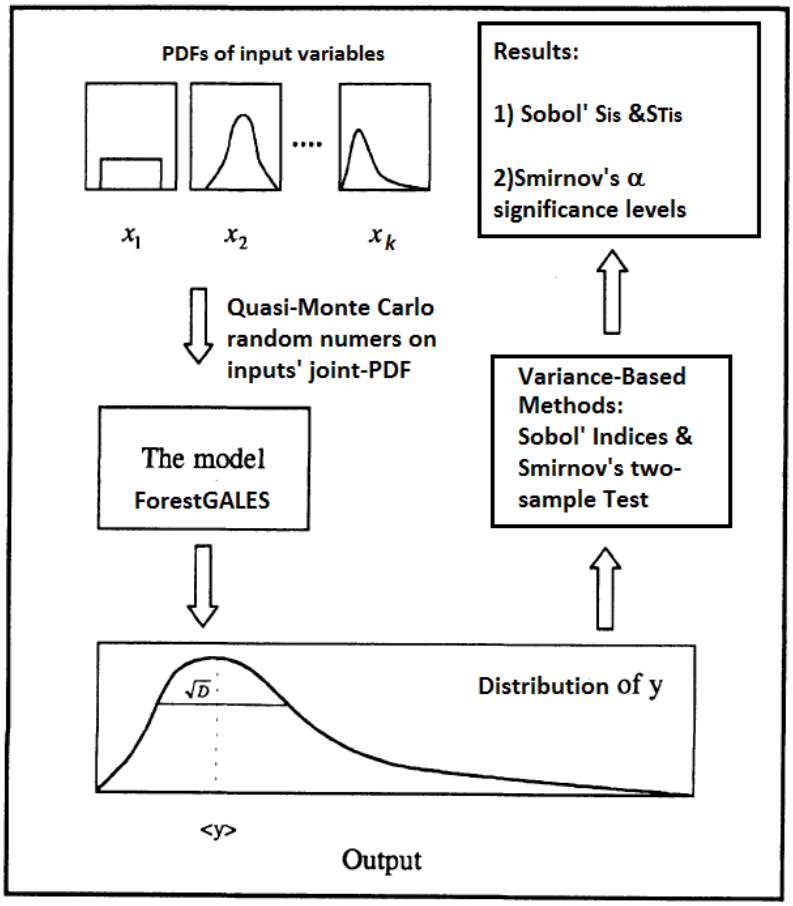
2.3.4.3.4 Settings for Global Sensitivity Analysis

In order to properly and successfully perform a GSA, the modeller is required to clearly define the objective of the analysis (Saltelli et al., 2000). Four scenarios, or settings, are available to aid with this requirement: Factor Prioritisation, Factor Fixing, Variance Cutting, and Factor Mapping (Saltelli et al., 2008). The settings differ in their methods and their objectives. The term "*factors"* is here used *in lieu* of "*variables"*.

Factor Prioritisation is adopted to identify which variables, once fixed to a nominal value (e.g. their mean), result in the larger reduction of the variance of the output. This is done by ranking the input variables according to their first-order effects S_is while neglecting interactions between variables. Factor Prioritisation is a useful tool for researchers, as it aims to provide insight on which factor(s) require more accurate measurements or further analysis on the basis of their first order effect on the variance of model outputs.

Factor Fixing aims at simplifying the structure of a model to make it more computationally efficient and can make communication of the inner workings of a model to its stakeholders more straightforward. In principle, following this analysis it might be possible to condense an entire section of a model to a fixed value if all the variables involved in the specific section are not influential. This setting allows fixing the un-influential variables to their nominal value without affecting the output's variance or imposing any restrictions on the desired value of the output. It requires the calculation of total sensitivity indices.

Variance Cutting and Factor Mapping are similar to the FORM methods described in section 2.3.4.2. Variance Cutting aims at achieving a lower variance of the output by fixing the smallest amount of variables to their nominal value. Factor Mapping is basically a form of Monte Carlo filtering, in that it divides the output space into "acceptable" and "unacceptable" regions and allows the identification of those variables which are mostly responsible for realisations of the model into each region, and those which "trigger" the switch between regions. Therefore, in this setting the analyst is not concerned with the output variance, but rather in the acceptable and unacceptable regions of the PDF of the output. However, a variable with a low value of S^T_i is unlikely to be flagged as influential under the Factor Mapping setting (Saltelli et al., 2008). Applying this to ForestGALES, it is fortunate that the model outputs are binary, as described in section 2.1.5, as this makes Factor Mapping conceptually easier to perform. For this setting, I have assumed that when the probability of damage is equal or larger than 0.1, the model predicts damage to a stand: an "unacceptable" behaviour. Conversely, when the probability is smaller than 0.1, I have assumed no damage, or an "acceptable" behaviour. Here damage is intended as either breakage or overturning. This analysis is done with m independent Smirnov two-sample, two-sided tests, carried out on the two cumulative probability functions of each X_i, marginal on the acceptable and unacceptable output regions, respectively (Saltelli et al., 2000; Saltelli et al., 2008). For the study presented in Chapter 5, Factor Prioritisation, Factor Fixing and Factor Mapping were the settings chosen for the sensitivity analysis of ForestGALES. This approach is shown in Figure 2.7.



<Y> is the output's mean and $\sqrt{D}$ is the output's standard deviation.

Figure 2.6 - Schematic representation of the GSA used in this study (adapted from Saltelli et al., 1999).

2.3.4.3.5 Investigating differences between species

In ForestGALES, the variable "species" serves as a trigger for species-specific modules which contain the calculations of tree characteristics such as canopy dimensions, and the values of MOE, MOR, wood density, and C_{reg}. It is of interest to use statistical methods to explore the differences between the species, if any, in the variables that drive most of the output's variance. This information might help simplifying the model and make it more generally applicable. For example, should these differences be insignificant, fieldwork requirement for the parameterisation of ForestGALES for new species might be largely simplified, and large-scale applications of the model in areas with heterogeneous species composition would be more easily defendable. To this aim, in Chapter 5 I have adopted a method based on the coefficients of concordance as described by Iman and Conover (1987) and Helton et al. (2005)

to compare the importance ranking of input variables between species. The method is described in detail in Chapter 5.

In the next Chapter I present the parameterisation of ForestGALES for *E. globulus*, accompanied by an evaluation of the performance of the parameterisation against the available data on wind damage to *Eucalyptus* spp. with regards to different planting densities and the presence/absence of a windward gap. A global sensitivity analysis of this parameterisation completes the following Chapter.

Chapter 3 Parameterisation and evaluation of ForestGALES for *Eucalyptus globulus*

3.1 Introduction

Species of the genus *Eucalyptus* are some of the most widely adopted in commercial plantations worldwide, primarily for the production of biomass for the pulp and fibre board industries (Diaz-Balteiro and Rodriguez, 2006). Whilst the proportion of biomass extracted from Eucalypt plantations for the global pulp and bioenergy markets is already prominent, it is likely to increase in the future (Gardiner and Moore, 2014). The attractiveness of this genus for commercial purposes is due to its fast growth rates, high productivity, good stem form, good adaptability to different environmental conditions, predisposition to hybridisation and cloning, and natural tendency to sprout vigorously when coppiced (Campinhos, 1999; Giménez et al., 2013; Goncalves et al., 2008). Eucalypt plantations currently provide 50% of the world's wood fibre (FAO, 2007), most of which is produced in South American countries. For instance, in Brazil Eucalypt plantations are planted on an area of 4.7 M ha (ABRAF, 2011), generating ~7.5 M tonnes of pulp per year (Diaz-Balteiro and Rodriguez, 2006), almost equivalent to the country's entire annual wood fibre production (Sedjo, 1999). In Brazil, the mean annual increment (MAI) of *Eucalyptus* spp. under current silvicultural practices is typically around 40 m^3 ha^{-1} y^{-1} (Binkley and Stape, 2004), with recorded maxima of 90 m^3 ha^{-1} y^{-1} in small trial plots (Eldridge et al., 1994). The typical rotation length ranges between 6 – 7 years (Diaz-Balteiro and Rodriguez, 2006). *Eucalyptus globulus* (Labill.) is one of the most successfully adopted plantation species in areas other than the tropics because of its fast growth, high pulp quality, and adaptability to sub-tropical and temperate climates (Campinhos, 1999; Sasse and Sands, 1997; Potts et al., 2004). After being introduced in Europe in the 19th century (Leslie et al., 2011), this species has been increasingly used in commercial plantations in the Iberian Peninsula for the production of biomass for pulp and bioenergy (Diaz-Balteiro and Rodriguez, 2006; António et al., 2007). The high density of its wood makes this species particularly sought after for bioenergy purposes (the Forest Products Commission of Western Australia reports a typical value of green wood density of 1040 kg m^{-3}). In Portugal, *E. globulus* is planted on over 26% of the nation's forested area (~812,000 ha), making it the predominant tree species in the country (Águas et al., 2014; Dias and Arroja, 2012). In Spain, *E. globulus* plantations are mostly concentrated in the Northern regions of Asturias and Galicia (Riesco-Muñoz, 2004). In the Iberian Peninsula the typical

rotation length is 10 – 12 years, generating yields between 10 m^3 ha^{-1} y^{-1} and 50 m^3 ha^{-1} y^{-1} (António et al., 2007; Riesco-Muñoz, 2004), with MAI of 10 – 15 m^3 ha^{-1} y^{-1} (Diaz-Balteiro and Rodriguez, 2006).

The vulnerability of *E. globulus* plantations to environmental hazards such as fire and pests has been extensively studied (e.g. Moreira et al., 2009; Águas et al., 2014; Wingfield et al., 2008), while the occurrence of wind damage is poorly documented. Trabado (2009) reports that 45% of the timber volume damaged by storm Klaus in 2009 in the north-west Spanish region of Galicia (total damage: 1.2 - 1.8 Mm^3) was to *E. globulus* trees. In the same year, in Uruguay, two violent tropical cyclones caused damage to approximately 10% of a private 27,000 ha Eucalypt plantation, corresponding to financial losses of 10 M US$. It is uncertain what Eucalypt species were affected. However, Campinhos (1999) and Vallejos-Barra et al. (2014) report on the extensive use of *E. globulus* in Uruguay. The fact that in the decade preceding such events no wind damage to the plantation had occurred made these massive losses unpredictable from an historical point of view. For these events, data on tree and stand characteristics are not available. I am aware of only three peer-reviewed papers in the literature (WIliams and Douglas, 1995; Gerrand et al., 1997; Chen, 2003) where wind damage to Eucalypt stands are reported together with some data on tree and stand characteristics, although the wind speeds responsible for the damage are available only in the latter. These studies are further discussed later in this Chapter.

Wind is the main cause of abiotic disturbance to forests in temperate and boreal biomes (Schelhaas et al., 2010). European meteorological records of the frequency and severity of extreme winds show a marked increase during the last three decades (e.g. Hanewinkel et al., 2011), as do the records of storm-damaged timber. Part of this increase is due to the larger volume of standing timber in European conifer forests -and hence the amount of timber at risk (Schelhaas et al., 2003). In addition to this, climate model simulations show a tendency for increasing magnitude, and sometimes frequency, of extreme wind events worldwide (Haarsma, 2013; Solomon, 2007). The largest European losses resulted from the Vivian/Wiebke storms in 1990 (with more than 100 M m^3 of timber volume losses), the Lothar/Martin storms in 1999 (which is to date the most damaging storm recorded in Europe, with losses of almost 200 M m^3), the Gudrun storm in 2005 (75 M m^3), and the Klaus storm in 2009 (42 M m^3) (Bavard et al., 2013; Blennow et al., 2010; Kilpelainen, 2010; Schindler et al., 2012; Schuck and Schelhaas, 2013; Usbeck et al., 2010; Wohlgemuth et al., 2002). Besides

Europe, forests in other parts of the world have been severely affected by windstorms, most notably the USA (Uriarte and Papaik, 2007, Beach et al., 2010), Japan (Kamimura and Shiraishi, 2007), New Zealand, Fiji, and Australia (Everham and Brokaw, 1996; Moore and Watt, 2015). However, studies of wind damage in South America are scarce, with a few notable exceptions. Negron-Juarez et al. (2010) and Marra et al. (2014) report the extensive damage caused by a single cross-basin squall event in 2005 to a Central Amazon forest, which resulted in the loss of about 30% of the forested area in the region, estimated to about 23% loss in mean annual biomass accumulation.

The large wind-induced losses experienced in European conifer forests have stimulated scientific research on wind damage to forests. Statistical methods have been widely used in the literature, correlating stand properties and tree position within a stand with frequency and severity of wind damage (Albrecht et al., 2012). As recently reviewed by Hanewinkel et al. (2011), the main shortfall of statistical approaches is the inability to generalise the findings of one specific study to other cases, due to the large variations in the geography, topology, and species from one case to another. In fact, these methods do not provide any information on the processes involved, but do indicate the key variables controlling wind damage risk (Kamimura et al., 2015). Since the end of the 20th century this approach has been complemented by process-based, semi-mechanistic models such as ForestGALES and HWIND (Gardiner et al., 2008). Process-based models allow me to use tree and stand characteristics to calculate the critical wind speeds that would result in tree breakage or uprooting (Gardiner et al., 2000). Therefore, these models are transferable to different forest stands, rather than being restricted to a specific case, provided that the models are suitably parameterised. For instance, ForestGALES was developed to predict wind damage to British coniferous trees (Gardiner et al., 2000), and has subsequently been successfully adapted to a broad range of coniferous species in other parts of the world: France (Cucchi et al., 2005), Japan (Kamimura, 2007), and Canada (Byrne et al., 2005). A practical advantage of process-based models is that they can aid forest managers to minimise the risk of wind damage, by informing on species suitability and best silvicultural practices (Peltola, 2006).

Besides the forestry sector, the issue of wind damage to plantations is relevant for forest insurance. As the demand for wood fibre and the moratoria on harvesting mixed tropical hardwoods have forced forest companies to establish plantations, the number of forestry and plantations projects seeking insurance from damage due to natural hazards has

increased steadily in the last 10 years. In terms of wind damage, the perceived unpredictability of catastrophic wind events, and the lack of methods to estimate risk in the absence of historical data, have restricted insurers from providing clients with coverage against wind-induced losses. The lack of wind loss data has been an important issue as wind damage is infrequent but often catastrophic, unlike fire losses that have a high frequency and usually low impact (Phil Cottle, pers. comm.). The importance of quantifying environmental risks to commercial plantations is particularly evident when the current pressure on natural forests to provide ecosystem services (e.g. biodiversity, soil and water conservation) is considered. In fact, by maximising the productivity of planted forests, the requirement for extracting timber and other wood products from natural forests can be greatly reduced (Sedjo, 1999). The development of process-based models of wind damage has largely focussed on conifer species, which are extensively managed in boreal and temperate regions. At present, a number of spruce, fir, and pine species are featured in these models, with birch the only broadleaf (in the HWIND model, Peltola et al., 2000). Because of the general scarcity of historical data on wind damage to Eucalypt plantations, and in light of their commercial importance and wide geographical distribution, species of this genus are ideal candidates for the application of process-based models for predicting their level of risk to wind damage.

Towards this aim, in this Chapter I parameterise ForestGALES for *E. globulus* grown under environmental conditions typical of the Northern Spanish region of Asturias, and evaluate the model's behaviour in regards to the presence/absence of a windward gap, and a range of planting densities. I compare model behaviour with the few records of wind damage in eucalyptus forests. In line with good modelling practice, I include a sensitivity analysis, an essential ingredient for validation and corroboration of any model-based assessment. In the Methods section of this Chapter I describe the fieldwork requirements for the parameterisation, and the adopted methods for the evaluation of model behaviour and sensitivity analysis. In the Results section I present the results of the parameterisation and model performance, and of the sensitivity analysis. I close the Chapter with a discussion of the value of the model for evaluating wind damage risk to eucalyptus.

3.2 Materials and Methods

The ForestGALES wind-risk model, the procedures for the measurements of the mechanical properties of wood samples obtained from the test trees, and the calculations of the critical bending moments, are described in the previous Chapter. In this section I provide details on the fieldwork performed for the collection of the data utilised for the parameterisation of ForestGALES for *E. globulus*.

3.2.1 Data collection for parameterisation: *Eucalyptus globulus* tree pulling in Asturias

Tree-pulling was carried out in November 2014 on 24 trees of *E. globulus* in the Asturias region in northern Spain to obtain the necessary data for the parameterisation of ForestGALES. Figure 3.1 shows the location of the site and a picture of one of the pulled trees being prepared for the experiment. The experimental site is located at 6°11'43.00"W, 43°28'29.20"N, and has an elevation of 282 meters asl. The terrain of the experimental area is flat, with a predominant soil classified as Agro-ecological Class VI, Edaphic, Aquic Dystrudept and Typical Dystrudept (acidic, well-drained soils). The area is characterised by mild temperatures, without important limitations for vegetation (Papadakis' Agro-climatic index II (Papadakis, 1966)). The annual precipitation is 996mm, with an average of 161 days per annum with rainfall >0.1 mm. Frost days happen rarely more than twice per year. Monthly average temperatures range between 7 and 23 ^{o}C, with a mean annual temperature of ~14 ^{o}C. The prevailing winds are westerly and south-westerly. The forest used to be populated with a range of conifer species before *E. globulus* was introduced some 50 years ago to provide pulpwood for the local paper industry (Ernesto Alvarez, personal communication). The stocking density at the site was 741 trees ha^{-1} at age 24.

24 trees equally divided in three dominance classes, from within diameter ranges based on quartile data were randomly selected from the site. I followed the pulling method described in Nicoll et al. (2006) except for the following slight differences:

1. Three inclinometers were used: one at tree base, one at the pulling cable attachment height, and one halfway between the two;

2. The attachment height of the pulling cable was lower than half tree height and varied from tree to tree. The objective of the study was to uproot the trees rather than breaking them, to obtain C_{reg} values for ForestGALES.
3. Crown dimensions were measured prior to pulling, by visually projecting the maximum lateral extent of the canopies in the four cardinal directions to the ground, and measuring the horizontal distance from the base of the tree;
4. Pulleys were used to increase the force for large trees, or when another tree was used as a pivot because of site restrictions.
5. For uprooted trees, three measurements of root depth were taken, at each of the 2 lateral extremities of the exposed root plate, and close to the tree base. Maximum rooting depth was difficult to establish, but was measured as the distance between the tree base and the furthest coarse root (diameter > 0.5 cm) that had become exposed. Root rot was recorded if present.

Details of all the equipment used are given in Appendix A. The method of Nicoll et al. (2006) was used to obtain the stem green density, and the masses of the canopy and the stem. The volume of the stem was calculated as a series of tapered columns of 1 m length.

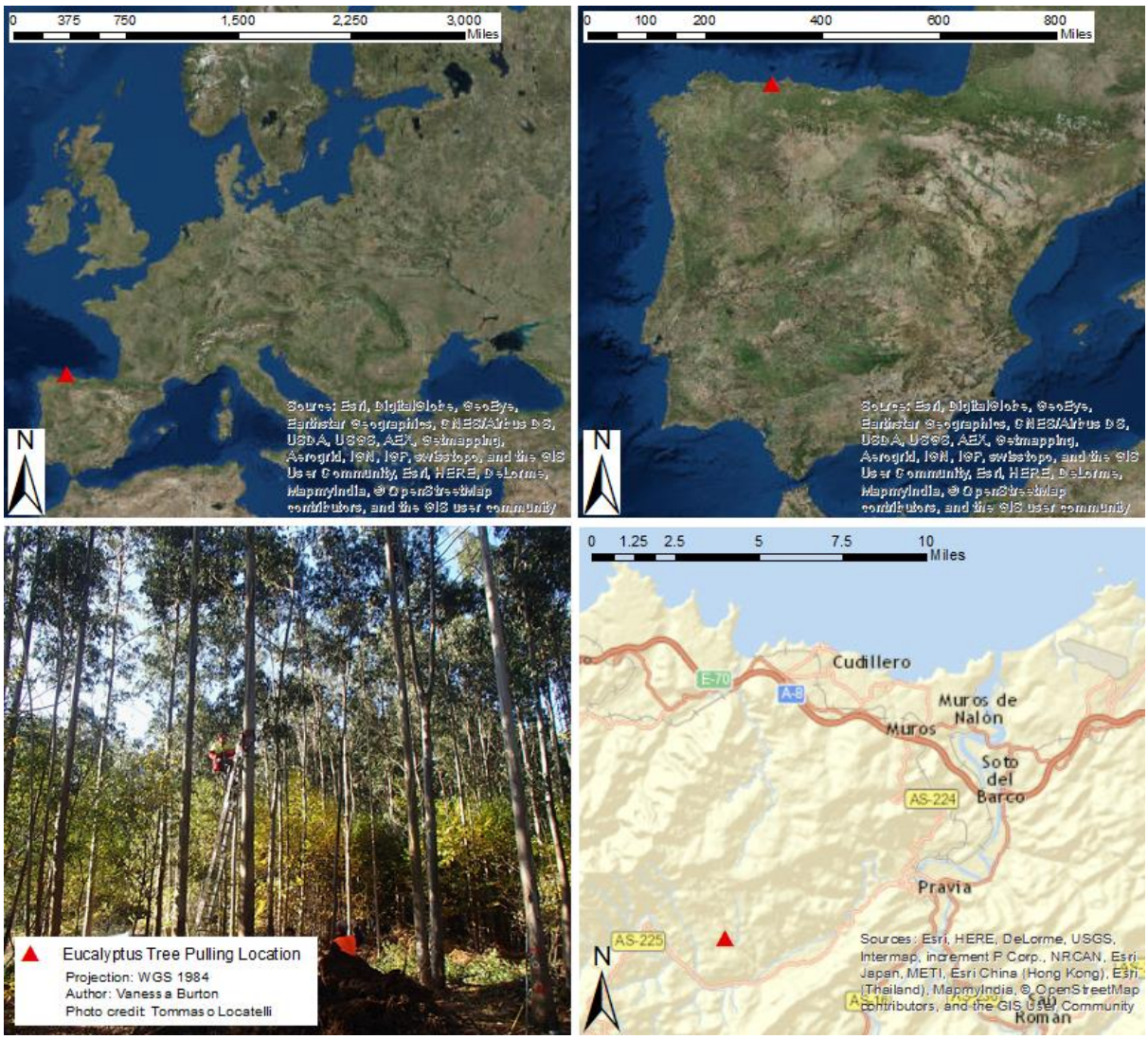


Figure 3.1 - Geographical location and appearance of the experimental *E. globulus* stand.

3.2.2 Data Processing for model parameterisation

3.2.2.1 Crown streamlining parameters

Modelling of crown streamlining is fundamental to the calculation of critical wind speeds, as the wind drag acting on the canopy is a function, amongst other things, of the crown area exposed to the wind. Because of the lack of wind tunnel measurements for the streamlining of the canopy of *E. globulus*, parameters to model crown behaviour under wind loading were extrapolated from black cottonwood (*Populus trichocarpa* Torr. & A. Gray) data in Vollsinger et al. (2005). This species was chosen because of the similarities of its canopy with *E. globulus* in terms of morphology and leaf area density. ForestGALES uses two parameters, *C* and *N*, to model the drag coefficient of the tree's crown (Eq. 3.1).

$$\boldsymbol{Drag\ Coefficient = C * u^{-N}} \quad \textbf{(3. 1)}$$

where *C* is the value of the drag coefficient at rest, *N* is the exponent that describes the power fit to the data, and *u* is the wind speed of interest (m s^{-1}). The drag coefficient is used to adjust the tree frontal area in the calculation of z_0 and *d*.

3.2.2.2 Canopy dimensions parameters

The parameterisation process requires measurements of canopy width and breadth for the calculation of the canopy's frontal area and canopy volume. The latter is used in combination with canopy weight for the calculation of canopy density. Canopy depth was calculated by subtracting the height of the lowest live whorl from the total height of the tree. Calculation of canopy breadth required approximation of the irregular elliptic shape of the canopies to regular ellipses, using the crown vertical projections as described in Section 2.2. To parameterise ForestGALES, canopy depth and canopy breadth were regressed against mean tree height and *Dbh* (see Table 3.4).

To obtain crown volume for canopy density calculations, the sectional area of the canopy was calculated under the assumption that *E. globulus* canopies are ellipsoid-shaped. Because the canopy of most trees was not centred on the stem's vertical axis, the crown sectional area of the canopy was assumed to be shaped as the sum of 2 half-ellipses (e.g. the "Northern" and the "Southern" half-ellipses), and calculated with Eq. (3.2).

$$\boldsymbol{Sectional\ area = \frac{\pi}{4} * (N + S) * (E + W)} \quad \textbf{(3. 2)}$$

where the capital letters indicate the distance between the tree base and the projection of the crown to the ground in each corresponding cardinal direction.

3.2.3 Evaluation of model behaviour

Throughout this section and the rest of the Chapter, to differentiate between when I discuss tree height, dbh, sph, and gap as model variables, and when I refer to them as tree or stand characteristics, I will denote the former with a capital letter and italics (i.e. "*Tree Height*", "*Dbh*", "*Sph*", and "*Gap*"). The scarcity of wind damage data to *Eucalyptus* spp. in the literature makes validation of this version of ForestGALES difficult. Ideally, data from forest

inventories of damaged *E. globulus* stands, and the damaging wind speeds should be known for a number of windthrow events to perform a proper validation. Therefore, I have decided to investigate the behaviour of the model in regards to *Tree Height* and presence/absence of a windward *Gap* for a range of planting densities. I discuss my findings by comparing them to the only three papers in the peer-reviewed literature that report wind damage to Eucalypts: Williams and Douglas (1995), Gerrand et al. (1997), and Chen (2003).

3.2.3.1 Investigating the behaviour of my parameterisation of ForestGALES

The investigation of the behaviour of this parameterisation of ForestGALES was performed for simulated *E. globulus* trees growing under climatic and environmental conditions typical of my experimental site. To obtain tree-input parameters for ForestGALES, I used the environmental and climate data reported in section 3.2.1 with a modified version of the GLOBULUS model (Soares et al., 2006). The GLOBULUS model calculates dominant height and mean diameter of *E. globulus* trees. Typically, ForestGALES converts automatically top height to mean height with species-specific equations using regression parameters from multiple stands data. However, this was not possible for my study because of my small sample size. Similarly, I could not determine the dominant dbh from my data. Therefore, to obtain mean tree height for my ForestGALES simulations, I used the only formula amongst those presented by Soares and Tomé (2002) to calculate mean height in a *E. globulus* stand that does not require knowledge of the dominant dbh. This formula calculates mean tree height as a function of dominant tree height and mean dbh. In fact, because the latter is calculated in GLOBULUS from the total basal area of the stand, calculation of mean height is also a function of sph. While Soares and Tomé advocate the use of this formula only for young trees (<4 years), and suggest a different equation for older trees, they also show that for trees of height > 5m the relationship between the two is basically linear, and that the disagreement is minor. GLOBULUS requires knowledge of the Site $Index_{10}$ (SI_{10}), i.e. the average dominant height at 10 years, to describe the productivity class of a site. Although data on the geographical distribution of the SI_{10} of *E. globulus* in Asturias are scarce, based on the work of Merino et al. (2003) SI_{10} values in the region are believed to range between 10 and 30. The mean height of my sampled trees was ~23m (see Table 3.3 in the Results section of this Chapter), and dendrometric measurements suggested an average tree age of 24 years. Calculations of mean tree height with the formula of Soares and Tomé (2002) suggested that

15 was an appropriate SI_{10} value for my site. I present my results for trees older than 3 years. Using GLOBULUS and the formula of Soares and Tomé (2002), this corresponds to a tree height of ~3.7m. To model the canopy of young *E. globulus* trees, I set a condition in ForestGALES that for trees shorter than 5m, canopy depth is calculated as half of tree height. This is representative of the young *E. globulus* trees that were found at the experimental site. For trees taller than 5m, canopy depth is modelled with the regression equation shown in Table 3.4 in the Results section. Based on data from my experimental site, I set the upper limit of tree height at 25m for the simulations. Mortality was removed from GLOBULUS in order to test the model for fixed stocking densities.

Soil type and rooting depth could not be changed because I only have one regression between *SW* and resistance to uprooting (based on the tree pulling at my experimental site). I simulated my stands for presence/absence of an upwind gap because this is known to make a forest stand more prone to wind damage (e.g. Somerville, 1989). Wind climate data was not used as an input because I adopted an intermediate output of ForestGALES, the CWS that is able to cause tree failure. This allows investigation of the impact of stand and site characteristics without the complication of wind climate. I did not discriminate between modes of failure: my final model output was the lower of the two CWSs. These factors mean that the sensitivity of the model's output to soil type, rooting depth, and wind climate were not investigated.

3.2.3.2 Data for model evaluation

I evaluated the model by comparison to three published studies on wind damage to *Eucalyptus* spp. I extracted data about tree, stand, and -where available- wind speeds that resulted in wind damage, from the papers of Williams and Douglas (1995), Gerrand et al. (1997), and Chen (2003). The relevant data from these studies are summarised in Table 3.1.

Table 3.1 - Data on tree and stand characteristics and wind speeds from the three evaluation papers. S*ph*: stems per hectare; *MAI*: Mean Annual Increment (m^3 ha^{-1} yr^{-1}).

Reference	Tree height	Stocking density	Upwind gap	Max Wind Speed	Comments
Williams and Douglas (1995)	Damage threshold suggested at 9m.	N/A	N/A	N/A	Study area included 3 *Eucalyptus* spp. (not including *E. globulus*). Taller trees more exposed to damage.
Gerrand et al. (1997)	Dominant stand height between 28m – 30m at age 11.	Initial stocking >1,300 sph, thinned to 900 sph and 300 sph.	Present, associated with damage.	N/A	*E. globulus*. Highly productive site (*MAI* = $30m^3$/ha/yr). Damage occurred (7% of stand) after late thinning. Slender trees due to high initial stockings and late thinning suggested as more prone to wind damage.
Chen (2003)	Between 6m and 8m, equally distributed between plots.	3 plots: 3,333 sph; 1,666 sph; 1,111 sph.	Not specified but likely present (coastal plots).	32.6 m/s	*Eucalyptus* spp. *urophylla* and *urophylla* X *grandis* hybrid. The study refers to typhoon damage in the Leizhou Peninsula in China. Very young trees (1 to 2 years). The higher the stocking density, the more resistant the stands.

Based on the stocking densities reported in the evaluation papers (Table 3.1), I decided to run ForestGALES for the following scenarios, which include the planting density of my experimental site (see section 2.2.1): 300 sph; 741 sph; 900 sph; 1110 sph; 1300 sph; 1650 sph; 3300 sph. *Gap* size was fixed to 0 or 250m to simulate absence and presence of a gap, respectively. The maximum value of *Gap* (250) was chosen because in ForestGALES there is no impact for gaps larger than 10 times mean tree height and a gap size of 250m covered the entire range of *Tree Height* in my study.

3.2.4 Global sensitivity analysis

For the purpose of this Chapter, I performed a variance-based global sensitivity analysis (GSA) of the version of ForestGALES used in this Chapter for *E. globulus*, as described in the previous

section. I focus my GSA on the input variables of ForestGALES. I used the method of Kucherenko et al. (2012) for the calculation of first-order and total sensitivity indices in the case of correlated variables, because of the high correlation between *Tree Height* and *Dbh* (Pearson correlation coefficient $\simeq 0.91$).

I fitted probability density functions (PDFs) to my experimental dataset to calculate distribution parameters for *Tree Height* and *Dbh*. However, the small size of my dataset meant that choosing the appropriate distribution was problematic, as different types of distributions described the data equally well, based on Akaike Information Criterion values. Of the PDFs that fitted the data, I chose to describe *Tree Height* and *Dbh* with normal distributions, because the calculations of the sensitivity indices with the method of Kucherenko et al. (2012) are more straightforward for normal distributions. For *Sph*, I decided to adopt a uniform distribution ranging from 300 sph to 3300 sph, as per Table 3.1. I chose to describe *Gap* with two different distributions. I chose a binomial distribution with values 0 and 250 (i.e. no gap vs large gap, defined for my range of *Tree Height* as reported in Table 3.3), as well as a uniform distribution within the same range. While the choice of allowing *Gap* to vary uniformly within its range allows for a more complete exploration of the input space, for forest managers it is very often convenient to differentiate between whether a large gap is present or not. Table 3.2 shows the range of values of the four inputs used in the sensitivity analysis. I calculated the sensitivity indices with 21,350 model executions, sufficient for the indices to converge to their true value using the quasi-random method of Sobol'.

Table 3.2 - Range of values used for the generation of random samples samples from the probability distribution functions of the inputs. *sd*: standard deviation; *Dbh*: diameter at breast height, *Sph*: stems per hectare; *Gap*: size of the upwind gap.

Input Variables	Distribution	Parameters		Units
Tree Height	Normal	Mean: 23.17	sd: 4.59	Meters
Dbh	Normal	Mean: 21.78	sd: 7.52	Centimetres
Sph	Uniform	Min: 300	Max: 3300	Nº of stems
Gap	Binomial OR Uniform	Min: 0	Max: 250	Meters

3.3 Results

3.3.1 Model parameterisation

The values of the physical and biomechanical characteristics of the pulled trees, empirically measured for the parameterisation of ForestGALES during my tests on *E. globulus* in Asturias, are reported in Table 3.3.

Table 3.3 - Empirical values of tree variables for *Eucalyptus globulus* required for the parameterisation of ForestGALES. Field: measured directly during the experiments; Derived: calculated from field measurements; Laboratory: measured in a laboratory after completion of the pulling experiments; *MC*: moisture content. *sd*: standard deviation.

Variable, Acronym and Units	*n*	Min	Max	Mean	sd	Source	Comments:
Height (m)	24	15.6	32.2	23.18	4.69	Field	
Dbh (cm)	24	12.42	38.21	21.78	7.68	Field	
Stem volume (m^3)	24	0.097	1.458	0.45	0.39	Derived	
Stem weight (kg)	24	114.49	1580.36	513.61	415.88	Derived	
Green wood density (kg m^{-3})	24	982.32	2805.40	1229.81	394.43	Derived	
Crown weight (kg)	24	11	289	92.71	81.58	Field	
Crown density (kg m^{-3})	24	0.234	1.616	0.45	0.29	Derived	
Canopy depth (m)	24	3.5	15.3	8.22	3.21	Field	
Canopy breadth (m)	24	2.80	6.75	4.68	1.20	Field	
Tree lean at failure (degrees)	24	0.3	19.2	3.38	4.16	Field	Max: Tree 30 - Dominant; Min: Tree 46 – Sub-Dominant.
Modulus of Rupture – MOR (MPa)	111	99.45	156.40	122.49	12.05	Laboratory	MC~12%. On average, between 4 and 5 flitches from each tree.

Modulus of Elasticity – MOE (MPa)	111	11088.25	16472.00	13859.63	1514.27	Laboratory	MC~12%. On average, between 4 and 5 flitches from each tree.
Canopy loading (Nm)	24	215.99	8068.87	1698.32	2118.51	Derived	
Stem loading (Nm)	24	499.10	12857.02	2840.06	3322.52	Derived	
Total Turning Moment (TM) (Nm)	24	10047.12	257106.6	82224.75	71531.67	Derived	
Tree components TM (Nm)	24	716.13	19821.76	4538.38	5370.24	Derived	

From the values recorded in my experiments, as shown in Table 3.3, ForestGALES model parameters and formulas were calculated with the formulas described in sections 2.2 and 2.3. Table 3.4 shows the parameter values and equations used in ForestGALES.

Table 3.4 - E. globulus ForestGALES model parameters.

Parameter	**Formula / Value**	**R^2**	***p* – value**	**Comments**
Mean Height (m)	1.0 * Top Height	n/a	n/a	
Canopy Breadth (m)	0.138 * *Dbh* *100 + 1.764	0.73	< 0.001	Value of *Dbh* in meters
Canopy Depth *A* (m)	0.405 * Mean Height - 1.163	0.35	0.002	Original form of ForestGALES regression
Canopy Depth *B* (m)	-0.53 * Mean Height + 0.6257 * *Dbh* + 6.872	0.72	< 0.001	Improved regression
Canopy Depth *C* (m)	0.5 * Mean Height	n/a	n/a	When Mean Height < 5m
Stem Density (kg m^{-3})	1229.81	n/a	n/a	
Canopy Density (branches + leaves: kg m^{-3})	0.45	n/a	n/a	
Modulus of Rupture (MPa)	105.65	n/a	n/a	Calculated. MOR of green wood
Modulus of Elasticity (MPa)	1244.76	n/a	n/a	Calculated. MOE of green wood
Knot Factor	1	n/a	n/a	
C	3.03	n/a	n/a	Graphically extrapolated from Vollsinger et al., (2005)
N	1	n/a	n/a	Graphically extrapolated from Vollsinger et al., (2005)
Root Bending Term	0	n/a	n/a	
C_{reg} with Tap Root *(N m kg^{-1})*	164.1	0.98	< 0.001	n=7
C_{reg} without Tap Root *(N m kg^{-1})*	162.32	0.94	< 0.001	n=14

C_{reg} with Rot in Root System *(N m kg^{-1})*	156.52	0.99	0.003	n=3

The values in Table 3.4 are used in the *E. globulus* species-specific parameter file of ForestGALES for my simulated stands, as shown in the next section. The R^2 of the regression formula normally used in ForestGALES to calculate canopy depth from mean height (formula *A*) is quite low (0.35, *p*-value < 0.01). However, this R^2 is within the range of the conifer species already included in ForestGALES (e.g. Ruel et al., 2000). However, including *Dbh* in the regression formula (B) increased the fit to the data (R^2=0.72, *p*-value < 0.001). It should be noted that, while the R^2 of the regressions for the Overturning Moment Multipliers (C_{reg}) between stem weight and critical turning moment are very high, they were however calculated from very small samples. The values of C_{reg} for the different rooting systems (evident presence of tap root *vs* absence of tap root *vs* presence of rot) are displayed in Figure 3.2. I could not assess the rooting system in the 2 trees that snapped. However, because their values for *MOE* and *MOR* did not differ from those of the trees that failed by overturning, I assumed that their rooting was highly resistant, and I grouped them with the trees with a tap root.

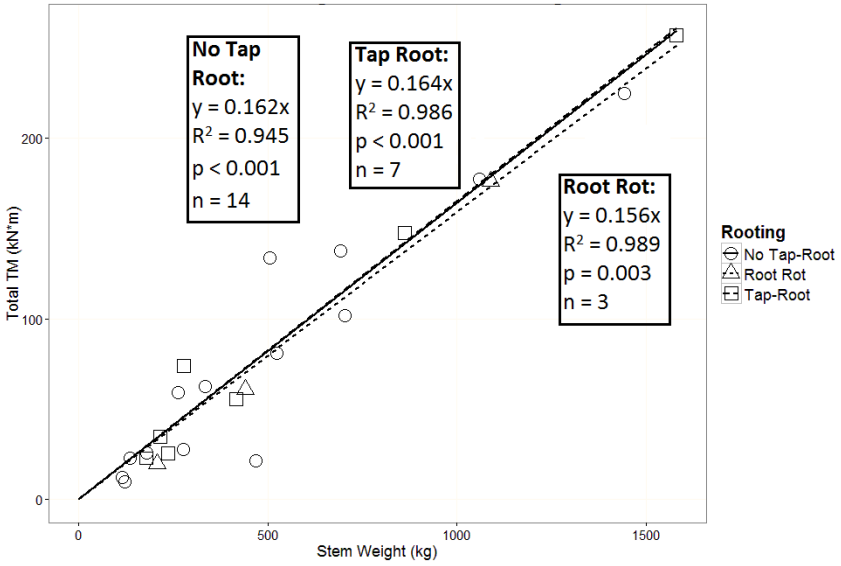


Figure 3.2 - Effect of changes in rooting on resistance to overturning of *E. globulus*.

The scatterplot in Figure 3.2 shows the relative unimportance of the architecture and integrity of the rooting system for my *E. globulus* trees, for which the presence of a tap-root

does not seem to influence tree resistance to overturning. In fact, the two regression lines for tap-root and no tap-root almost overlap. Similarly, the trees for which rot in the root system was recorded do not differ from those without evident rot. Despite the very small number (*n*=3) of pulled trees which exhibited root rot, the validity of this finding is corroborated by the fact that their stem weights are well distributed across the ranges of Stem Weight and Total Turning Moment. A final confirmation of the low importance of the quality of the rooting system in my experiment is provided by an Analysis of Covariance (ANCOVA) where the total turning moment is the response variable, stem weight the continuous explanatory variable, and the type of rooting is a factor with the three levels described above. Indeed, the differences between the types of rooting are confirmed to be non-significant (*p*-value = 0.806). For this reason, in my simulations I only adopted one value of C_{reg} (162.3 N m kg^{-1}, for trees without a tap-root, selected because it was calculated from a larger dataset (see Table 3.4).

3.3.2 Model evaluation

3.3.2.1 Investigation of model behaviour

The results of my ForestGALES simulations for *E. globulus* stands at increasing stocking densities, in the presence/absence of a windward *Gap*, are shown in Figure 3.3.

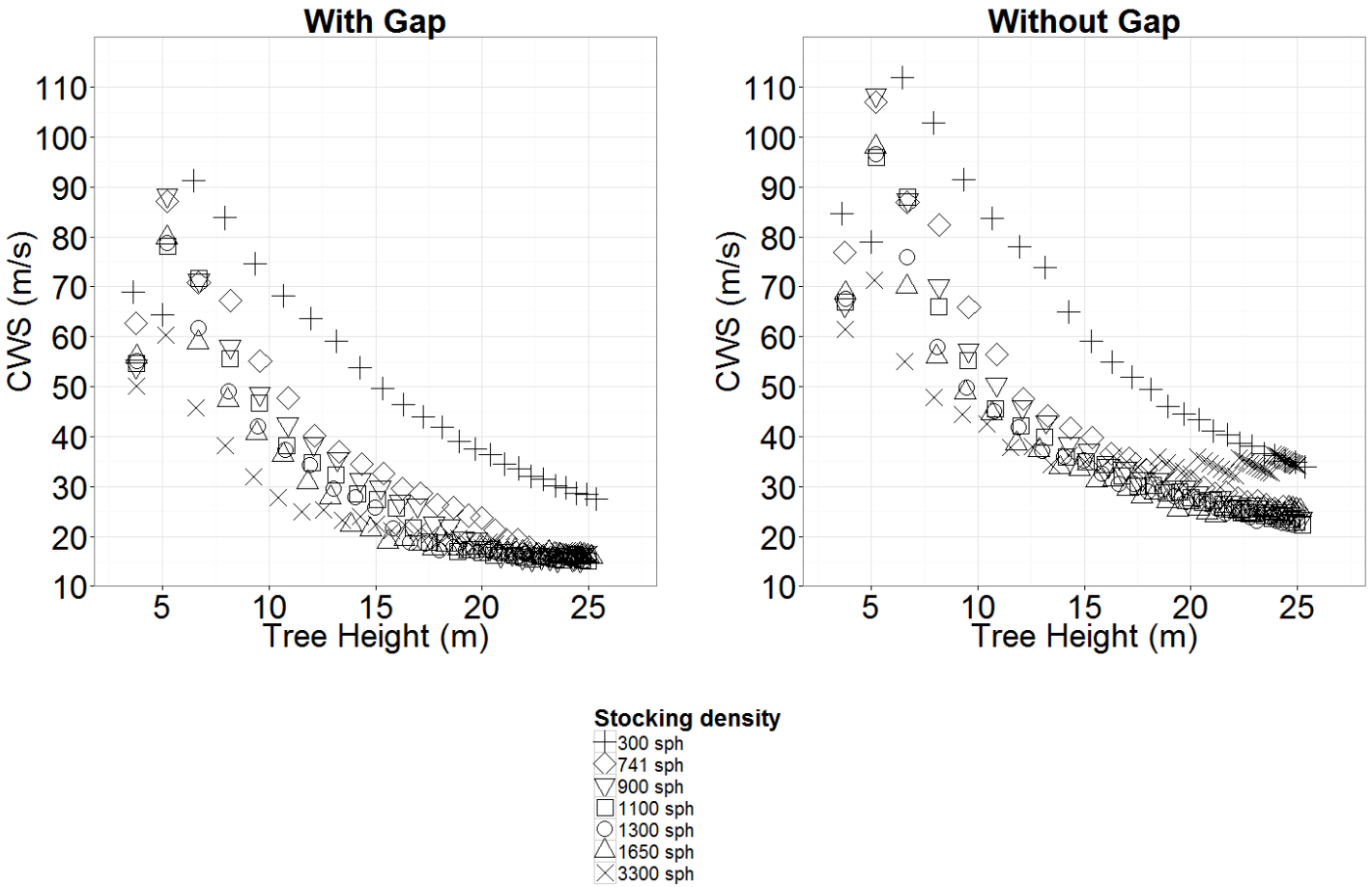


Figure 3.3 - Scatterplots of critical wind speeds as a function of tree height and stocking density, in the presence and in the absence of a large windward gap, as calculated with ForestGALES.

As shown in Figure 3.3, in the presence of an upwind *Gap*, for trees taller than 5m and for all the stocking densities, the critical wind speeds calculated for my virtual stands monotonically decrease (i.e. the stands are more prone to wind damage) as *Tree Height* increases. This finding is in agreement with the well-known tenet that, regardless of their species, trees become more prone to wind damage as they grow taller (e.g. Gardiner et al., 2000). For small trees (height < 5m) my CWS are lower than for trees immediately past this height, as seen in the peaks on the left of the scatterplots. This behaviour is independent of the stocking density used, although it becomes less marked as the density increases, probably due to the form (i.e. the taper) of my simulated trees under different stocking densities. As a word of caution, ForestGALES has not been parameterised to date for short trees. Therefore, my results for trees shorter than 5m fall outwith the confidence range of application of ForestGALES, and should be regarded as tentative extrapolations. As shown in Figure 3.3, CWS decrease more rapidly from a *Tree* Height of about 6 – 15m. The effect of spacing is also evident, with decreasing CWS as stocking density increases. The scatterplots show that for stocking densities over 900 sph the CWS *vs Tree Height* curves level off asymptotically past a certain *Tree Height*. This threshold becomes lower as stocking densities increase (for stocking densities above 900 sph). I ascribe this behaviour to the increasing *Tree Height*/*Dbh* ratios for increasing stocking densities, as calculated with GLOBULUS and the method of Soares and Tomé (2002). This behaviour is also reflected in the boxplots in Figure 3.4, where the quartiles of the CWS distributions become narrower as the stocking density increases. The trends observed for the presence of an upwind *Gap* are also evident for stands not exposed to a large upwind *Gap* (scatterplot on the right of Figure 3.3). In the absence of a *Gap*, the calculated CWS are higher than for the scenario with a *Gap*, as can be noticed by comparing the two scatterplots in Figure 3.3: without a *Gap*, the curves shift upwards, corresponding to lower vulnerability to wind damage. As shown in Figure 3.4, this difference becomes larger as stocking density increases, as does its significance, as confirmed with two-tailed t-tests (*p*-values shown in Figure). For high stocking densities, the values of my calculated CWS fluctuate a little for taller trees (Figure 3.3). This model behaviour is particularly evident for stocking density = 3300 sph in the scenario without an upwind *Gap*.

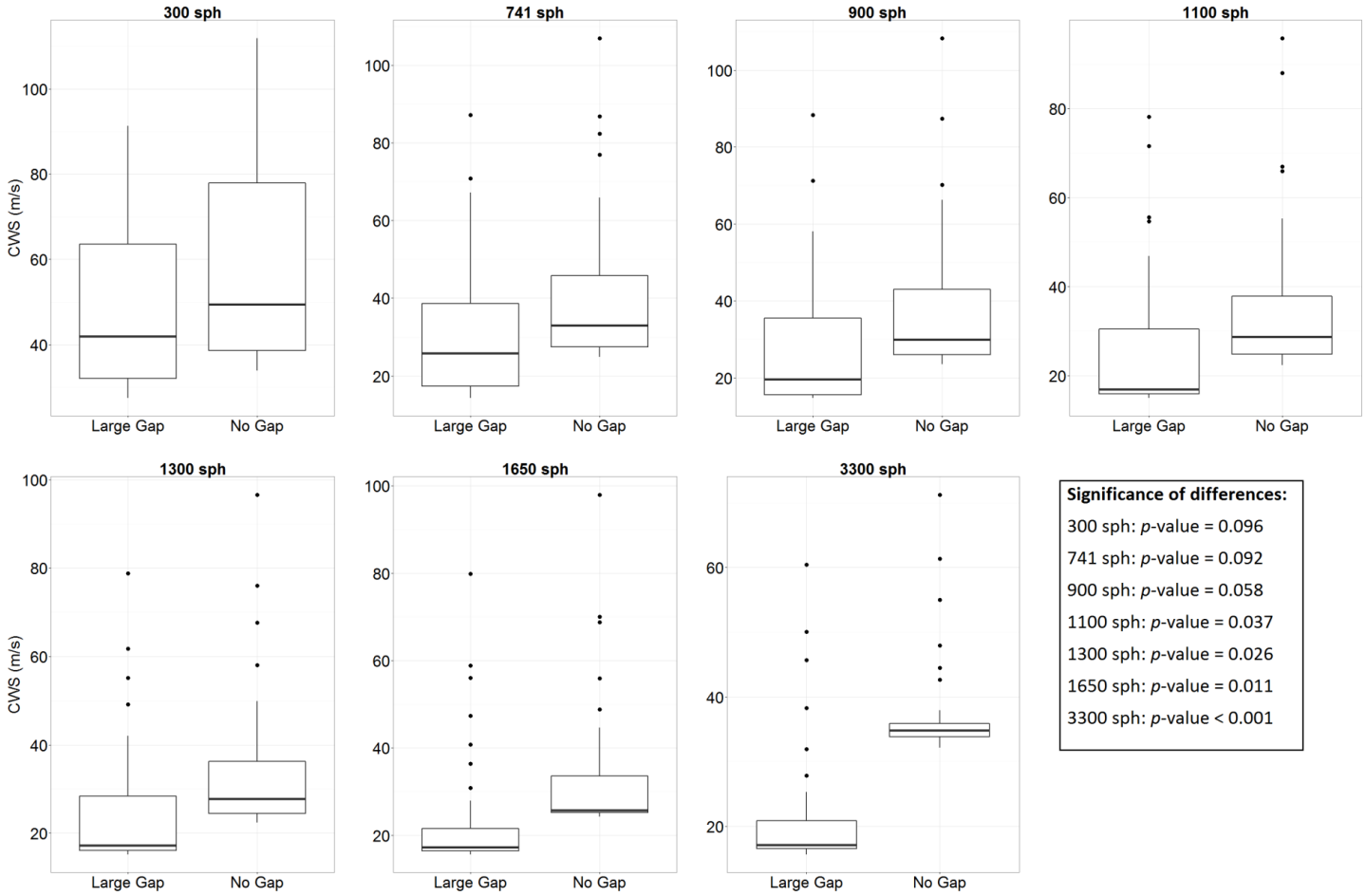


Figure 3.4 - Distributions of critical wind speeds by stocking densities and presence/absence of a windward gap. *p*-values denote the significance of the differences between presence/absence of a gap.

3.3.2.2 Model evaluation against literature data

The stocking densities 300 sph, 900 sph, and 1300 sph in Figure 3.3 (presence of *Gap*) are representative of Gerrand et al. (1997), while stocking densities 1100 sph, 1650 sph, and 3300 sph are similar to the plots in Chen (2003). Due to the lack of stocking and gap data in Williams and Douglas (1995) I could not relate any specific stocking density to the damage reported by the authors. My simulations generally agree with the threshold tree height of ~9m suggested by Williams and Douglas (1995), above which trees become more vulnerable to wind damage. However, in my simulations this is more evident for low to medium stocking densities (up to 1650 sph), where the risk of wind damage increases markedly (i.e. CWS decreases rapidly), as seen in Figure 3.3.

Gerrand et al. (1997) report that, for tall trees (height $\geq$ 25m) of taper within the range of 0.90 to 1.13, thinning from 1,300 sph to 900, and subsequently 300, increased the risk of wind damage in stands exposed to a gap. The values of taper are consistent with those of my simulated trees. The trend reported by Gerrand et al. (1997) is not evident in my simulations with an upwind *Gap*, as Figure 3.3 shows that tall trees are associated with lower CWS for high stocking densities than for very low stocking densities. This disagreement is likely to be due to the fact that - in the study of Gerrand et al. (1997) - thinning operations exposed trees that had not previously become acclimated to the wind, while in my simulations I did not focus on the effect of thinning on the vulnerability of a stand to wind damage. My model simulations do not fit well with the young Eucalyptus trees data in Chen (2003). The author reports that a max wind speed of 32.6 m s^{-1} caused 10 – 50% cumulative damage to their stands, the level of damage being inversely proportional to the stocking densities. Both graphs in Figure 3.3 show that my simulations calculated CWS in excess of ~45m s^{-1} for *Tree Height* between 5 and 10m for medium stocking densities (1100 sph), while CWS for tree height within this range decrease markedly as *Sph* increases.

3.3.3 Sensitivity analysis

The results of the Global Sensitivity Analysis for uniformly and binomially distributed values of *Gap*, using the method of Kucherenko et al. (2012) for correlated variables, are displayed in Figure 3.5a and 3.5b for first order and total sensitivity indices, respectively.

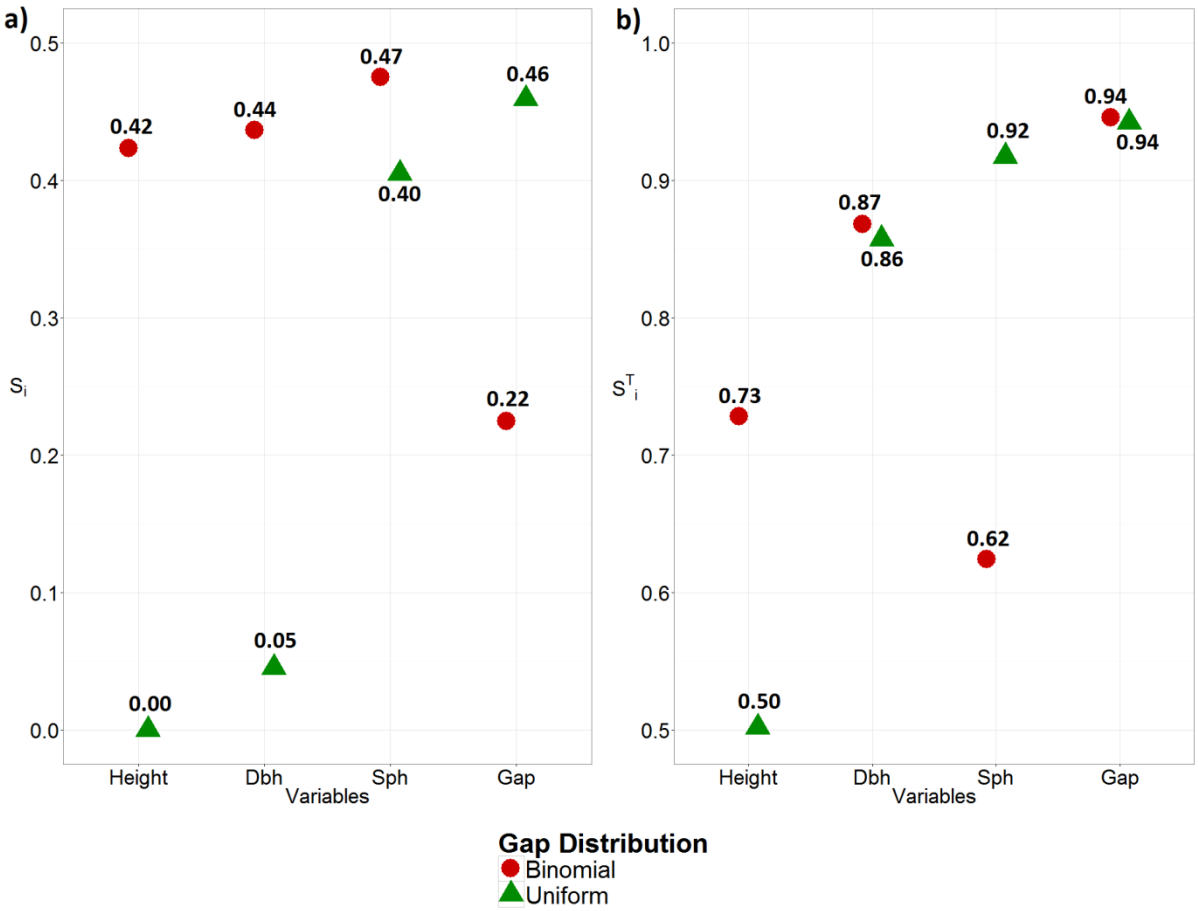


Figure 3.5 - Sobol' First Order (a) and Total (b) sensitivity indices for uniformly and binomially distributed values of Gap. Note difference in scales on the ordinate

The complex interactions between the four input variables used in my sensitivity analysis of ForestGALES are evident from Figure 3.5, as seen from the large differences between the values of the first-order (S_i) and the total (S^T_i) sensitivity indices. This result indicates that the number and the size of the interactions between the inputs are large, and that the behaviour of the model with regards to my inputs is nonlinear. Knowledge of the exact size of an upwind *Gap* has also a large effect on the contribution of the input variables to the variance of the output. When I allowed *Gap* to vary uniformly between 0m and 250m, the direct importance of *Sph* and of *Gap* itself outweighed that of *Tree Height* and *Dbh*, as measured by their S_i values (Figure 3.5a, *Gap* Distribution: Uniform). However, the large differences between the S^T_i and the S_i of *Tree Height* and *Dbh* when *Gap* was uniformly distributed suggest very significant interactions particularly between the two variables, and all the four variables overall (Figure 3.5a and 3.5b, *Gap* Distribution: Uniform). In contrast to this, the results of the analysis where the only values of *Gap* were the extremes of its distribution show that

Tree Height, *Dbh*, and *Sph* were the main drivers of the variation of critical wind speed, in almost equal measure (Figure 3.5a, *Gap* Distribution: Binomial). This corresponds to the practical case when the exact size of an upwind gap is not known, and gap is defined as either present or absent. Under the scenario of a binomially-distributed *Gap*, the interactions between the inputs are less marked than in the case of a uniformly-distributed *Gap*. This is especially evident for *Dbh*, whose interactions with the other variables were the most enhanced of all the inputs when *Gap* was described by a uniform distribution. In the simulations when *Gap* was distributed binomially, the interactions involving *Sph* were the least significant, while the extreme values of *Gap* amplified its importance in driving the variation of the output (Figure 3.5b, *Gap* Distribution: Binomial).

3.4 Discussion

In this study, I have performed a parameterisation of the wind-risk model ForestGALES for *E. globulus* from field data acquired in a monospecific forest in Asturias, Spain. This is the first time that this model has been parameterised for a broadleaved species. I focussed on *E. globulus* because of its prominence in the pulp and biomass industry sectors worldwide, including the Iberian Peninsula, where *E. globulus* stands were accessible and available for my experimental work. To model *Tree Height* for different stocking densities I used the growth model GLOBULUS (Soares et al., 2006), together with a formula proposed by Soares and Tomé (2002) which calculates mean tree height as a function of dominant tree height and mean dbh. The scarcity of detailed wind-damage data to *Eucalyptus* spp. means that attempting to validate my parameterisation would not have been a rigorous process. Instead, I have investigated the behaviour of my parameterisation of ForestGALES for different stocking densities with scatterplots of the critical wind speeds calculated by the model against *Tree Height*. I also attempted to evaluate whether my model predictions fit logically with the observed damage to *Eucalyptus* spp. as reported from three studies found in the literature (Williams and Douglas, 1995; Gerrand et al., 1997; and Chen, 2003). For my investigation and evaluation of model behaviour I have simplified the model's structure by fixing those input variables for which I had no variation in my experimental plot (Rooting Depth, Soil Type). In accordance with sound modelling practices, I have provided a sensitivity analysis of the model, using the method of Kucherenko et al. (2012) for correlated variables,

an extension of the variance-based method of Sobol' (Saltelli, 2002). Below I carefully scrutinize the major steps in my analysis.

3.4.1 Model parameterisation

To perform the parameterisation for *E. globulus* I followed the methods used for coniferous species already included in ForestGALES (e.g. Ruel et al. (2000), Elie and Ruel (2005), Nicoll et al. (2006)). I found that, by including *Dbh* in the modelling of canopy depth, I was able to considerably improve the fit of my regression. This simple adjustment is of relevance to the practical applications of ForestGALES, for which limiting the input variables to those normally recorded in forest inventories is paramount. This is the first instance that ForestGALES has been parameterised for a broadleaved species, and challenges in the modelling of tree characteristics are expected. Because of the differences in crown morphology between conifers and broadleaves, modelling of canopy dimensions and streamlining is likely to be one of the major challenges for other broadleaves to be included in the model. My approach of modelling the crown of *E. globulus* trees as an ellipsoid, from data obtained by visually projecting the breadth of the canopy to the forest floor, provides a first attempt. Time constraints during tree-pulling fieldwork need to be accounted for, as this method is more time-consuming than the traditional approach of measuring the crown after a tree has been pulled over. In my parameterisation I used the streamlining parameters calculated by Vollsinger et al. (2005) for black cottonwood, a species of similar crown shape as *E. globulus*. Ideally however, more experiments like that of Vollsinger et al. (2005) would be required to investigate the streamlining and drag of broadleaves crowns, especially given the differences in leaf size in broadleaves and the resulting effect on drag.

My experiment was designed to have a range of tree sizes. Hence, the large variations in some of the recorded variables reflect the differences between tree dimensions across the three dominance classes. It is interesting to note how *MOR* and *MOE* are not affected by the same degree of variation, suggesting that tree size and dominance class do not have a sizeable impact on *MOR* and *MOE*. My mean value of *MOE* is lower than those reported by Yang and Evans (2003) (*MOE*≃18 GPa) and Wentzel-Vietheer et al. (2013) (≃18.6 GPa), but very close to that reported by McKinley et al. (2002) (≃13.7 GPa) for *E. globulus*. The mean value of the *MOE* of my trees (13.9 GPa) is very similar to that of *Eucalyptus diversicolor*

(F.Muell.) reported in the FPL Wood Handbook (Bergman et al., 2010) and of *Eucalyptus pilularis* (Sm.) in Lavers (2002). My *MOR* value is in agreement with Yang and Evans (2003) (*MOR*≃119 MPa) and with McKinley et al. (2002) (122 MPa). The values of the density of green wood of the *E. globulus* trees in McKinley et al. (2002) is in very good agreement with my data (1229.81 kg m^{-3}).

There are a number of limitations in my study. Since I gathered field data on only one site, this does not allow variation of soil types for my data analysis. Similarly, I did not measure soil moisture. However, there is currently no agreement in the literature on the role of soil moisture in tree anchorage (e.g. Dunham and Cameron, 2000; Cucchi et al., 2004; Kamimura et al., 2012). Both soil type and water availability are associated with *E. globulus* root development (e.g. Fabião et al., 1995). However, the soil of my experimental site was not waterlogged at the time of the survey, which suggests that my experimental trees had optimal anchorage. The importance of the root-soil system is more evident in poorly drained soils or soils with a hardpan, which are not favourable for the development of sinker roots or taproots, resulting in a shallow rooting depth (Peltola, 2006). Under such circumstances, an emphasis on roots developing radially and laterally would increase the anchorage of the tree (Nicoll and Ray, 1996). In my experiment I attached the winch cable below the standard half-tree height traditionally used in tree-pulling experiments (Nicoll et al., 2006) because I expected the *E. globulus* trees on my site to break along their stem rather than overturn under static pulling at half tree height. In order to calibrate ForestGALES for this new species I needed to ensure a number of overturned trees in each dominance class to perform the linear regressions to calculate the overturning moment multipliers (C_{reg}). Nicoll et al. (2006) found that deep rooting increased anchorage in conifer trees by 10 – 15%. Therefore, I expected that the presence of a tap root, which is known to be able to reach large sizes in *E. globulus* (Stone and Kalisz, 1991), would influence greatly the trees' resistance to overturning, but this did not appear to be the case in my study (Figure 3.2). It would be of great interest to investigate the resistance of *E. globulus* trees to uprooting in different soil types.

3.4.2 Investigation of the behaviour of my parameterisation

I investigated the behaviour of my parameterisation for different stocking densities and for climatic and environmental conditions typical of my experimental plots. As seen in the scatterplots of critical wind speed (CWS) *vs Tree Height* (Figure 3.3), trees of height lower than 5m are associated with lower CWS than those immediately above this threshold. However, critical wind speeds are known to be negatively correlated with tree height (e.g. Somerville, 1989), and previous applications of ForestGALES to conifer species have accurately reproduced this tenet (e.g. Gardiner et al., 2000). The aberrant behaviour of my parameterisation of ForestGALES for small *E. globulus* trees is then probably due to my decision to model the depth of the crown of short trees as half of tree height (see Table 3.4). In addition to this, as previously discussed ForestGALES has not been parameterised yet for short trees, which means that my results for trees shorter than 5m should be approached cautiously. There are small fluctuations in the CWS calculated for high stocking densities, as shown in Figure 3.3. In my interpretation, this behaviour is due to the calculation of mean tree height with the formula of Soares and Tomé (2002): for high stocking densities and tall trees, the calculation of tree-taper results in some small fluctuations, which propagate through ForestGALES to produce the fluctuations in my calculated CWS. The significant influence of tree taper on the CWS calculated with ForestGALES is discussed in Chapter 5. As expected, the contribution of an upwind gap in the calculations of CWS is maintained in my parameterisation. In fact, in the absence of acclimation to wind, trees exposed to a newly formed gap are known to be more susceptible to wind damage (Somerville, 1989). As shown in the boxplots in Figure 3.4, my virtual stands exposed to a gap are associated with lower CWS than those without a gap. The role of *Gap* in the calculations of CWS becomes larger as *Sph* increases, as shown in Figure 3.4. This is confirmed by the *p*-values in Figure 3.4, which become increasingly significant as stocking density becomes larger. This behaviour of ForestGALES is due to the fact that both stocking density and the size of *Gap* are involved in the calculations of the maximum and mean bending moments acting on the average tree.

3.4.3 Model evaluation against literature data

My simulations did not reproduce well the wind damage described by Chen (2003). This might suggest that ForestGALES is currently unable to effectively simulate the susceptibility

of young/short *E. globulus* trees to wind damage. Besides the issues with the modelling of crown dimensions discussed in the previous section, there are two likely explanations for this. Firstly, there are very few young trees in the UK Forestry Commission's tree-pulling database that was used to derive empirical values for resistance to overturning in ForestGALES, because the model was built to aid in the management of mature stands against wind risk. Young trees have larger ratios of sapwood/heartwood, which reduce the density of the wood and its mechanical properties (i.e. *MOE* and *MOR*), and hence probably behave differently than mature trees under wind loading. Secondly, very short trees result in values outside the confidence range for model calculations of some key parameters of ForestGALES that control the wind loading on a mean tree in a stand (e.g. spacing/height). However, the percentages of damaged young trees in the study by Chen (2003) are lower than 5% in all the plots (i.e. not significantly different from the annual mean in undisturbed plots in the area) but one, where 12.5% of the stand was damaged. ForestGALES assumes all trees in a stand to be equal to the mean tree, and can only predict catastrophic damage (~40%) or no damage at all (Hale et al., 2015). In addition to this, the *MOE* and *MOR* of the *Eucalyptus* spp. in the paper by Chen (*E. urophylla* and hybrid *E. urophylla* X *E. grandis*) are considerably lower than for *E. globulus* (Gonçalves et al., 2013). Because the calculations of the critical bending moments in ForestGALES include *MOE* and *MOR*, lower values of these parameters would result in trees more susceptible to wind damage (i.e. lower CWS). Gerrand et al. (1997) suggest that mature, tall trees (> 25m) become more susceptible to wind damage when stocking density decreases if thinning is not done early to promote larger dbh/height ratios. While my simulated trees of similar taper seem in agreement with this, especially for stands without a gap (Figure 3.3), I did not explore the behaviour of my parameterisation for very tall trees. Moreover, I did not investigate the effect of thinnings in my virtual stands. Thinning practices favour the penetration of wind inside a stand, exposing trees that relied on mutual support from neighbouring trees (and hence did not grow acclimated to such wind action) to higher wind forces. While ForestGALES can simulate thinnings, it is not able to deal explicitly with mutual support. However, my simulations show that lower stocking densities are associated with higher CWS (i.e. stands with wider spacing are at lower risk of damage), which is consistent with the findings of Achim et al. (2005) in their study of balsam fir's (*Abies balsamea* (L.) Mill.) resistance to windthrow. My results also agree with the existence of a threshold tree height above which CWS decrease steeply and monotonically, as proposed by Williams and Douglas (1995). From the forest manager viewpoint, my simulations suggest

that a safe approach would be to plant *E. globulus* seedlings at high densities and carry out an early thinning of mid-intensity before the stands reach a height of ~ 10 – 15m, to provide an initial return on planting costs, and to make the stands more stable. Stands should then be harvested before they reach a height of ~22 - 25m to reduce the risk of a large wind-caused loss. This is particularly relevant in areas that are susceptible to high wind speeds, and for stands recently exposed to an upwind gap. Ruel et al. (2000), in their parameterisation of ForestGALES for balsam fir suggest a similar approach for exposed stands. As shown in Figures 3.4 and 3.5, trees at the edge of a stand exposed to a gap have lower CWS than those within a stand or not exposed to a gap, regardless of stocking density.

Given the large variety of *Eucalyptus* spp. commercially planted worldwide, and their associated characteristics and climatic optima, it is of great interest that ForestGALES is parameterised for other species in the *Eucalyptus* genus. This is all the more important as the minimisation of wind-risk to commercial plantations can allow for more secure and higher productivity, and hence alleviate the requirement of exploiting natural forests and their resources for the timber and pulp industries (Gardiner and Moore, 2014), ensuring the provision of ecosystem services such as soil and water protection. Furthermore, *E. globulus*' resistance to wind damage needs to be compared with that of other species currently used in commercial plantations. One such species is *P. pinaster*, widely grown on the Iberian Peninsula and in south-western France. An associated article has been submitted, in which I compare the susceptibility of these two species to wind damage using ForestGALES for soil and wind climate conditions typical of the Aquitaine region of France.

3.4.4 Sensitivity analysis

By performing my sensitivity analysis with the variance-based method of Kucherenko et al. (2012), I was able to determine the sensitivity of the output of ForestGALES to my four input variables. Using the method of Kucherenko et al. (2012) for correlated variables is especially important since *Tree Height* and *Dbh* are naturally highly correlated, and using the original method of Sobol' (Saltelli, 2002) would have miscalculated the proportion of the output's variance explained by the input variables. My analysis has shown that – in my parameterisation of ForestGALES for *E. globulus* – the calculations of critical wind speeds are characterised by a high degree of non-linearity, and that the interactions between my four

input variables are numerous and complex, as shown by the large differences between total and first-order sensitivity indices (Figures 3.6a and 3.6b). These interactions are particularly evident for *Tree Height* and *Dbh* when the exact size of a windward gap is known (i.e. when I described *Gap* with a uniform distribution). Given the well-known strong correlation between tree height and wind damage (e.g. Gardiner and Quine, 2000; Peltola 2006), I expected my analysis to identify *Tree Height* as the main driver of variation of the model's output. However, when *Gap* was distributed uniformly, the direct contribution of *Tree Height* and of *Dbh* were outweighed by those of *Gap* and *Sph*, as opposed to when *Gap* was binomially distributed, when *Tree Height* and *Dbh* were responsible for significantly larger portions of the output's variance (Figure 3.5a). However, the large values of S^T_i calculated for all the four inputs indicate that these variables are all approximately equally important, regardless of whether the exact size of a gap is known. From a wind-risk modelling standpoint, this suggests that all the variables should be retained in future versions of the model, given that the structure of the model itself remains significantly similar to the current version. From the point of view of practical applications of the model, my findings suggest that accurately knowing the size of an upwind gap, and the stocking density and the mean dbh of the stand, would provide more robust estimates of the calculated critical wind speeds. This is convenient, since with traditional fieldwork techniques it is easier to measure with similar accuracy these variables than tree height. However, this is true for homogeneous stands with respect to tree height, since ForestGALES assumes that all trees within a stand are equal to an ideal tree with the mean characteristics calculated with the formulas in Table 3.4.

In the real world, the size of a windward gap can have any values between 0 and "very large", rather than the extreme scenarios of *Gap* being either present or absent. These two cases correspond to the uniform and binomial distributions of *Gap* adopted in this Chapter, respectively. A number of studies (e.g. Somerville, 1989; Quine et al., 1995) report that the contribution of a windward gap in increasing the susceptibility of a stand to wind damage is most commonly experienced when a new edge is formed (e.g. following clear-felling of an adjacent stand), rather than when a gap was already present, which would give time to the trees to acclimate to the stronger winds at the forest edge. Similarly, the effectiveness of a dense edge in reducing the rate of wind loading, as well as the positive correlation between upwind gap size and wind loading on forest edges, are well known (Stacey et al., 1994; Gardiner et al., 1997). Because ForestGALES is not capable of directly simulating tree

acclimation to wind exposure in correspondence to a gap that was formed before the establishment, or at the early growth stage of a forest, for practical applications of the model it is useful to know the importance of a gap in driving the calculations of the critical wind speeds. When using variance-based methods of sensitivity analysis such as that of Sobol', the uncertainty associated with a binomially-distributed variable with values "*a*" and "*b*" is larger than that of a uniform distribution of the same variable defined between the same values "*a*" and "*b*". Therefore, it is expected that a binomially-distributed variable will have a larger contribution to the output's variance. However, in my case *Gap*'s S_i was larger for the uniform case than for the binomial (0.46 and 0.22, respectively). With regards to interactions between the input variables, the extreme values of *Gap*'s binomial distribution amplify the interactions between *Gap* and *Tree Height* and *Dbh*, while *Sph* was negatively affected (Figure 3.5b). The sum of the first order effect indices is positively affected by these artificially-induced interactions. Indeed, when I allowed *Gap* to vary uniformly within its range, $\sum S_i$decreased from 1.56 to 0.91. These seemingly unexpected behaviours are ascribable to the presence of a "trap" in the code of ForestGALES by which when a *Gap* is larger than 10 times *Tree Height*, *Gap* is replaced by a constant. In my simulations under the binomial case, this substitution was more likely to happen than in the uniform case, which likely reduced the *Gap*'s S_i.

Finally, my decision of hardcoding rooting depth and soil type to a fixed value, dictated by the uniformity of my experimental plots in Asturias, might have concealed the model's sensitivity to these variables. However, sensitivity analysis cannot help with this, as it cannot confirm whether the assumption of fixing certain variables to their nominal values is realistic or not, nor can it alert the modeller to an incorrect characterisation of a variable. The sensitivity of ForestGALES to the variables rooting depth and soil type is discussed in Chapter 5.

3.5 Conclusions

In this study I have presented a parameterisation of ForestGALES, a semi-mechanistic model of the risk of wind damage to forests, for *Eucalyptus globulus* (Labill.). My results show that the resistance to overturning at my experimental site in Northern Spain was not influenced by the presence or absence of a tap-root. This finding suggests that in soils that are not

waterlogged, the anchorage of *E. globulus* trees is likely not to be affected by the presence or absence of a tap-root. The evaluation of the behaviour of my parameterisation shows that modelling the shape of the canopy of *E. globulus* trees with an ellipsoid provides a good approximation to account for the drag of the wind on the trees canopies. Despite the additional fieldwork required for this, future parameterisations of ForestGALES for other broadleaved species might benefit from my approach. My results show that tree height and stocking density are negatively correlated with critical wind speeds (i.e. they are positively correlated with risk of wind damage), and stands recently exposed to a large upwind gap are at higher risk of wind damage, especially when stocking densities are high. Based on these findings, in order to reduce the risk of wind damage I suggest that owners and managers of *E. globulus* forests and plantations should favour stands with low-to-medium stocking densities, carry out an early thinning at around a height of 10 – 12m, and harvest the stands soon after they have reached ~20m in height. This is especially true in areas with an unfavourable local wind climate. Similarly, management of adjacent stands should be carried out in such a way that the creation of upwind gaps following harvests is minimised.

My global sensitivity analysis of the version of ForestGALES used in this study shows the complex interactions in the model's code between tree height, dbh, stocking density, and size of an upwind gap. Tree height unexpectedly was not the main driver of output variation but was still largely involved in the calculation of critical wind speeds. Therefore, in order to reduce the variability of the model outputs, efforts should be focussed on accurate measurements of dbh, which are more easily obtainable than tree height. Similarly, knowledge of the stocking density of a stand, and the size of any upwind gaps, would effectively improve the reliability of the model predictions. When differentiating between a large upwind gap and no gap, tree height significantly contributed to the calculation of critical wind speed. The findings should be of particular interest to forest managers and wind-risk modellers concerned with wind damage risk to *Eucalyptus* spp.

Chapter 4 Comparing *E. globulus* and *P. pinaster*

4.1 Introduction

The extent of wind damage to forests and plantations in Europe has increased over the last 50 years of the 20th century (Schelhaas et al., 2010). This is partly as a result of an increase in frequency and severity of extreme winds as reported by European meteorological records, as well of the extensive adoption of intensive modern silvicultural practices, and larger standing timber volumes exposed to environmental hazards (Hanewinkel et al., 2011; Jactel et al., 2009; Mickovski et al., 2005). In France, storm Martin of 1999 severely affected forests and plantations in the south-western Aquitaine region, with estimated timber losses of 26.1 Mm^3. Most of these losses were to *Pinus pinaster (*Ait.) plantations, equivalent to ~3.5 years of harvest in the region (Cucchi et al., 2004). It has been estimated that storm Klaus, which hit northern Iberia and southern France 10 years later in January 2009, was responsible for losses in France of between 1.34 and 1.77 billion Euros for its effect on *P. pinaster* plantations alone, a figure that comprises losses in market value, future value, reforestation costs, and indirect damage to the affected stands (Costa et al., 2009). The volume of windfall caused by storm Klaus has been estimated at about 43.1 Mm^3 (Gardiner et al., 2010). Despite the fact that recorded maximum wind speeds during Klaus did not differ greatly between Portugal, Spain, and France (Liberato et al., 2010), wind damage to the extensive areas of plantations of *Eucalyptus* spp. in the Iberian peninsula (>10^6 ha planted in the second half of the 20th century (Merino et al., 2003)) appeared to be substantially less. I am aware of only one published paper which reports wind damage caused by Klaus in Galicia, Northern Spain, suggesting damage to an area of 32,500 ha (Riera, 2011). Trabado (2009) provides additional details and reports volumes of timber ranging between 1.2 and 1.8 Mm^3, consisting of 55% *Pinus radiata* (D.Don) and 45% *Eucalyptus globulus* (Labill.). In addition to their destructive effects, storms Martin (1999) and Klaus (2009) share other important characteristics, such as storm development and storm path (Liberato et al., 2010).

Differences in vulnerability to wind damage between species are well known, with logistic regression analyses suggesting that conifers are more prone to damage than broadleaves, primarily due to the fact that during winter storms the latter are leafless, hence decreasing the drag exposed to wind (Hanewinkel et al., 2013). However, not all broadleaf species shed their leaves during winter (e.g. *Eucalyptus* spp.) and the size and flexibility of the crown are

important characteristics that affect vulnerability to wind damage (Mason and Valinger, 2013). The vulnerabilities of different tree species depend greatly on their suitability to the environmental conditions where they are planted, such as soil quality and depth of the water table (*ibid*.).

P. pinaster is an important timber and pulp species throughout southern Europe (Khuder et al., 2007). In France, most *P. pinaster* plantations are located in the Aquitaine region. They cover ~7% of French forested areas (> 890,000 ha) while providing 16% of national timber and pulp production (Cucchi and Bert, 2003; Cucchi et al., 2005). In France, *P. pinaster* is considered a fast growing timber species (Cucchi et al., 2004), with typical rotation length between 35 and 65 years (Trichet et al., 2009). Because of this, it is currently being considered as a potentially suitable species for biomass production for bioenergy production (Moreaux et al., 2013). When not constricted by soil impediments, *P. pinaster*'s rooting system is believed to provide resistant anchorage to windthrow (Khuder et al., 2007). It consists of a dense network of medium and fine roots, a tap root, and numerous sinkers, the role of which in the anchorage of the tree increases as the tree matures (Danjon et al., 2005). However, in shallow soils where the hardpan is close to the surface, the growth of tap root and sinkers is inhibited (Khuder et al., 2007). This inability of *P. pinaster*'s root systems to penetrate hardpan layers can result in weak tree anchorage and poor adhesion between the root system and the soil (Khuder et al., 2007). In their paper on *P. pinaster* wind-resistance in Aquitaine after storm Martin (1999), Cucchi and Bert (2003) report that trees growing in dry soil conditions, in the absence of a hardpan layer, were more prone to stem breakage than uprooting, suggesting better anchorage. The importance of soil properties in the development of the root system of *P. pinaster* has been confirmed by Danjon et al. (2005). Cucchi et al. (2005) found large differences in *P. pinaster* trees resistance to wind damage between soils without, and with, a root anchorage-limiting hardpan, and reported that uprooting is the most common type of wind damage in *P. pinaster* stands in Aquitaine.

E. globulus has quickly become an important commercial species in temperate areas due to its fast growth and pulp quality (Sasse and Sands, 1997) and it is the most widespread tree species in Portuguese forests, currently covering 26% of the nation's forested area (Águas et al., 2014), having recently surpassed *P. pinaster* as the predominant tree species in Portugal (Dias and Arroja, 2012). Because of *E. globulus*' very fast growth and high yield, its rotation length in the Iberian Peninsula is ~12 years. The ability of Eucalypt trees to grow very large

tap roots with the potential to extend to great depths to reach deep water tables is well documented (Robinson et al., 2006) and has given rise to much controversy, as these species have often been blamed for water shortages (e.g. Kardell et al., 1986). Indeed, water shortage in the summer months is the main limitation to their growth in Northern Iberia (Fabião et al., 1995), and both annual precipitation and the number of days with precipitation > 0.1mm drive most of the variation in the growth models currently available (Tomé et al., 2006). However, unfavourable soil conditions such as hardpan layers are likely to limit Eucalypts' ability to tap into aquifers, and should favour the development of radial supporting roots rather than a large tap root, as reported for conifer species (Ray and Nicoll, 1998). Research on the ability of different *Eucalyptus* spp. tap roots to penetrate hardpan layers is scarce, although Robinson et al. (2006) documented that small-sized mallee species of Eucalyptus are able to grow their tap roots past clayey sub-soils with densities up to 2.0 g cm^{-3}. *P. pinaster* and *E. globulus* share similar ecological requirements and geographical range, as well as proneness to fire (Moreira et al., 2009; Águas et al., 2014). In regards to environmental risks to Eucalypts, while research on risk of pest and fire damage is at an advanced stage (e.g. Moreira et al., 2009; Águas et al., 2014), little detailed information is available about the vulnerability of these species to wind damage, especially in Europe. In Chapter 3 (published as Locatelli et al., 2016) I have parameterised the process-based, wind risk model ForestGALES for *E. globulus* and I discuss wind damage to Eucalyptus stands. In south-western France, a hybrid of *Eucalyptus gunnii* (Hook.) and *Eucalyptus dalrympleana* (Maiden) has been successfully planted by private companies for about 30 years for pulp production (Moreaux et al., 2013). In the mid-2000s this hybrid, named *Eucalyptus gundal*, has received renewed interest for biomass production for woodfuel (Moreaux et al., 2013). It is planted in small parcels of land on about 2,000 ha with rotation periods of ~10 years for both pulp and biomass production (Melun, 2011). Experimental trials of *E. globulus* and *E. gundal* growth performance are currently undergoing at arboreta in Aquitaine, being planted most commonly from cuttings, a practice that can impair the growth of the tap root. Preliminary results show that *E. globulus* has marginally faster growth rates than *E. gundal*, but suffers from high mortality when winters are very severe (Céline Meredieu, *pers. comm.*). *E. gundal* shares both high water demand and good water use efficiency with other *Eucalyptus* species (AFOCEL, 2004) and is believed to be fairly resistant to cold winters (cold-hardy to -12°C, especially past the juvenile stage) and water scarceness (Melun, 2011).

Statistical methods to assess risk of wind damage in forests have been widely used and reported in the literature, correlating stand and tree properties, and tree position, with frequency and severity of wind damage (e.g. Albrecht et al., 2012). A good account of the standard statistical methods and their shortcomings in relation to wind risk (i.e. their lack of external validity) is given by Gardiner et al. (2000) and, more recently, by Lanquaye-Opoku and Mitchell (2005). Since the end of the 20th century, this approach has been gradually substituted with semi-mechanistic, process-based models such as ForestGALES and HWIND (Peltola et al., 1999; Gardiner et al., 2000; Hale et al., 2015). Process-based models allow the prediction of the critical wind speeds required to break or uproot trees as a function of mean and stand tree characteristics, thus providing insight on the impact of silvicultural practices on wind risk and how to minimise such risk (Peltola, 2006). ForestGALES calculates stem strength, wind loading, and tree bending mechanistically, while it uses empirical relationships to describe rooting resistance and crown dimensions. Tree position relative to an edge in the forest and the size of an upwind gap modify the wind loading (Gardiner et al., 1997, Stacey et al., 1994). Hale et al. (2015) recently reviewed this approach and provided details of the ForestGALES model, which is extensively described in Chapter 2 of this thesis.

When comparing the vulnerability of two species to wind damage, the climatic factors that influence a tree's resistance to wind damage, and future changes in global and regional climatic conditions, must also be accounted for. Specifically, the predicted increase in atmospheric and sea-level temperature (IPCC, 2014) will likely promote faster growth rates and shifts of the ecological niches of most commercial tree species, as well as changes in precipitation and wind patterns. For these reasons, it is paramount that the relationship between tree species and wind damage in affected areas is investigated. This could help to prevent future large forest losses and allow an increase in the productivity of tree plantations. By doing so, larger areas of natural forests, with their ability to provide ecosystem services that cannot be obtained easily from commercial plantations (e.g. soil and water conservation, biodiversity), can be more effectively preserved (Gardiner and Moore, 2014). Therefore, in this study, I aimed to answer the following questions:

1. Are there significant species differences between the critical wind speeds for overturning of *P. pinaster* and *E. globulus*?
    1.1. Should species differences be observed, do these have an effect on the optimal rotation of the two species to minimise their vulnerability to wind damage?

4.2 Material and Methods

4.2.1 Study overview

Here I present an overview of the study. The specific details of each process are provided in the following sections. I have addressed the aims of this study by means of computer simulations. I have modelled the growth of *P. pinaster* using yield tables from Lemoine and Decourt (1969) and Lemoine (1991). I have adopted the GLOBULUS growth model (Tomé et al., 2006) to simulate growth of *E. globulus*. For both species, I have modelled tree growth for fast and slow growth rates. For both species, and for each year in the rotations that I have simulated, I have used the thus generated data of tree height, diameter at breast height (*dbh*), and stocking density, to calculate the wind speeds that would cause the trees to overturn using the process-based wind risk model ForestGALES (Hale et al., 2015). I focussed on overturning because, as reported by Cucchi et al. (2005), overturning is the most common type of wind damage to *P. pinaster* trees in Aquitaine. For the simulations with ForestGALES, I have complemented the data from the growth models with additional stand data typical of the Aquitaine region. By combining the computed critical wind speeds with information on the wind climate in the Aquitaine region, I have obtained the return periods of damaging storms. From these return periods, I calculated the cumulative probabilities of damage for each species, for each year in the simulated rotations. I have statistically evaluated the differences between species with regards to the critical wind speeds of overturning (CWS), and the associated cumulative probabilities of damage (CPD). I have plotted the results of my simulations (CWS and CPD) against tree height, age, and stand yield, to identify critical values of these tree and stand characteristics with regards to stand management to minimise the risk of wind damage. For CWS, I have compared our simulations with the maximum hourly mean wind speeds recorded during storms Martin (1999) and Klaus (2009). All the wind speeds (CWS and of the storms Martin and Klaus) are calculated at 10m above the zero-plane displacement, i.e. the height at which the wind can be assumed to act on a single point within the canopy (Thom, 1971). This height therefore depends on the mean height of a stand. For CPD, I have analysed my results by comparing them to a cumulative damage threshold of 10%.

4.2.2 Modelling the growth of *P. pinaster*

The growth of *P. pinaster* trees was simulated for two yield classes (2 – fast, and 4 - slow), as in Lemoine and Decourt (1969). While the latter yield class (YC=4) describes the most common rotation length in Aquitaine, both yield classes are representative of Aquitaine situations (Lemoine, 1991). *P. pinaster*'s yield tables from Lemoine and Decourt (1969) only report values of mean tree height, *dbh*, stems per hectare (*sph*), and timber volume per hectare for ages: 12, 16, 20, 24, 28, 34, 40, 46, 54, and 62. For each of the two yield classes, values of these variables for intermediate tree ages were calculated with linear models of polynomial interpolations of orders up to 5, the best fit estimated by the smallest value of the Akaike Information Criterion (AIC) of each polynomial order. Values before 12 years of age were linearly extrapolated assuming *sph* at planting = 2,500, a figure most commonly used in Aquitaine plantations. Because in Aquitaine thinning operations are typically carried out on *P. pinaster* trees, I added thinning volumes at the relevant points in the rotation (see Appendix B for further details).

4.2.3 Modelling the growth of *E. globulus*

Values of tree height, *dbh*, *sph*, and mean timber volume per single tree of *E. globulus* trees were modelled with the GLOBULUS model (Tomé et al., 2006). The GLOBULUS model uses site-specific climate data (elevation, annual numbers of rainy days and of frost days, annual precipitation, and mean annual temperature) to simulate tree growth. These data for Aquitaine are described in section 4.2.4. GLOBULUS describes the productivity of a site with a Site Index$_{10}$ (SI_{10}), i.e. the average dominant height at 10 years. Values of SI_{10} for *E. globulus* chosen for my simulations were 10 (slow) and 20 (fast). While the value of SI_{10}=10 for the slow growth rate scenario of *E. globulus* was chosen conservatively, due to the absence of *E. globulus* plantations in Aquitaine, I cannot be certain that a value of SI_{10}=20 is realistic for this area. However, considering that Moreaux et al. (2013) reported a mean height of 15m (*sd*=1.5) for 5.5 year-old *E. gundal* plantations in the south-west of France, and that *E. globulus* trees normally grow faster than *E. gunnii* and *E. dalrympleana* (Neilan and Thompson, 2008; Leslie et al., 2012), it is safe to assume that in the absence of particularly harsh winters growth rates corresponding to SI_{10}=20 can be achieved for *E. globulus*. The GLOBULUS model only provides values up to tree age = 36, as the fast growth and short rotation lengths of *E. globulus* mean that managed stands normally are harvested before that

age. Table 4.1 shows the values of mean tree height and *dbh*, *sph*, yield per hectare, and age of the trees at the end of the rotations of the two species, for both the growth rates used in this Chapter. Full tables with values for all the years in the rotations are shown in Appendix B.

Table 4.1 - Values of mean tree height and dbh (diameter at breast height (1.3m)), stocking density (sph), volume of standing timber, and age of the trees at the end of the rotations of *P. pinaster* and *E. globulus*, for two different growth rates for each species

Growth Rates	Trees age (years)	Volume of standing timber ($m^3\,ha^{-1}$)	Top height (m)	dbh (cm)	sph
E. globulus: Site $Index_{10}$ (20=Fast; 10=Slow)					
SI_{10}=10	31	255.5	22.2	18.1	829
SI10=20	13	263.3	23.1	16	1052
P. pinaster: Yield class (2=Fast; 4=Slow)					
YC=2	62	514.5	27.8	47.8	193
YC=4	62	390.1	23.9	41.1	217

4.2.4 Study area

The Aquitaine region is located in SW France. The mean annual precipitation is 990mm, mainly concentrated during winter and spring (Cucchi et al., 2004). The number of days per annum with rainfall ≥0.1mm is 125, while average daily temperatures range between 5.8 and 20.2 ^{o}C (mean 12.7), with an absolute minimum of -16.4 in 1985 and an absolute maximum of 38.8 in 1990 and 1998 (Bordeaux-Merignac, Normales et records des stations météo de France – Infoclimat). Periods of intense frost are relatively rare, happening every 10 – 20 years (Benito-Garzón et al., 2013). The average altitude is 47m a.s.l. The soil is a sandy podzol (Trichet et al., 2009) with a discontinuous hardpan at a soil depth of 0.5 – 1.0m (Khuder et al., 2007). In terms of soil moisture, the most common soil class is humid moorland (~44% of total Aquitaine area) (Trichet et al., 2009). The wind climate is typically mild, and the prevailing wind direction is north-westerly (Khuder et al., 2007). The susceptibility of the simulated stands of both species to wind damage was measured for westerly winds alone (the wind direction during the peak of storms Martin and Klaus). The storms of 1999 and 2009 that caused large areas of windthrow were characterised by localised maximum hourly mean wind speeds of about 25 m s^{-1}, recorded at inland locations, although wind speeds of

up to 36 m s^{-1} were recorded along the coast (Bordeaux-Merignac, Normales et records des stations météo de France – Infoclimat).

4.2.5 Simulations with the wind risk model ForestGALES

ForestGALES is a process-based, semi-mechanistic model of wind-risk damage to forests that combines tree and stand level variables (tree species, height, *dbh*, *sph*, rooting depth, soil type, size of an upwind gap) to calculate the critical turning moments required to uproot or break the average tree in a stand. These critical moments are then translated into the critical wind speeds that would result in such moments by assuming that the force of the wind is experienced on a tree at a single point (the zero-plane displacement height) and that the energy of the wind is transferred to the trees by means of canopy drag (Raupach, 1994). Parameterisation of the model for a new species is done by means of tree-pulling tests, which are primarily aimed at the measurement of the resistive forces of the root/soil system. As described in Nicoll et al. (2006), the critical overturning moments are therefore calculated as the linear regression of stem weight and overturning moment (C_{reg}), forced through the origin, for different soil types and rooting depths. Because the trees pulled in the experiments aimed at parameterisation are typically taller than 10m, my results for trees of height between 5m and 10m are based on linear extrapolation. However, as discussed by Gardiner et al. (2000), the linear regressions of stem weight vs overturning moment are characterised by coefficients of determination (R^2) in excess of 0.9, which provides confidence to my extrapolation. Model parameters for my simulated stands of *P. pinaster* were acquired from Cucchi et al. (2005), and from Chapter 3 for *E. globulus.* The presence of a discontinuous hardpan in the soils in Aquitaine was accounted for by running the model simulations for 2 scenarios: shallow rooting (hardpan present) and deep rooting (hardpan absent), as in Cucchi et al. (2005). For *E. globulus*, I have used the C_{reg} values for presence and absence of a tap root (as reported in Chapter 3) to simulate absence and presence of a hardpan layer, respectively. I ran the simulations for a homogeneous soil type, as per section 4.2.4. The size of an upwind gap is a very important driver in the calculations of the critical wind speeds with ForestGALES, especially for stands that have been recently exposed (i.e. brown gaps), as shown in Chapter 3 in the section on the sensitivity analysis of ForestGALES for my parameterisation for *E. globulus*. As shown by Stacey et al. (1994), gaps larger than 2 to 4 times tree height result approximately in a two to four-fold increase in the bending moments

of trees at the edge of a brown gap. Above these values, the bending moments remain almost constant. Edge trees are known to require about 5 to 10 years to acclimate to the increased wind loading due to the creation of a new edge, e.g. by allocating resources to larger root systems (Nicoll et al., 2008). As reported by Kamimura et al. (2016), current silvicultural practices in Aquitaine result in brown gaps being common in the area, as harvesting practices seldom take the increased risk of wind damage that follows from the creation of brown edges. To account for the effect of gap, I ran my simulations with ForestGALES for the absence and presence of a large (>>4 times tree height, i.e. "infinite") gap. Therefore, in my simulations for the presence of gap, I assume that, at any time within a rotation, a gap has been only recently created. Table 4.2 summarises the combinations of species, growth rates, presence/absence of an upwind gap, and rooting depths (8 per species, for a total of 16 "virtual stands") used in my wind risk simulations.

Table 4.2 - Combinations of species, growth rates, presence/absence of windward gap, and rooting depth used for ForestGALES simulations for the calculations of critical wind speeds and cumulative probabilities of damage

Species	***Growth Rates* (Yield Class or Site Index)**	***Upwind Gap***	***Rooting Depth***
P .pinaster	Yield Class = 2	Present	Shallow
		Present	Deep
		Absent	Shallow
		Absent	Deep
	Yield Class = 4	Present	Shallow
		Present	Deep
		Absent	Shallow
		Absent	Deep
E. globulus	Site $Index_{10}$ = 20	Present	Shallow
		Present	Deep
		Absent	Shallow
		Absent	Deep
	Site $Index_{10}$ = 10	Present	Shallow
		Present	Deep
		Absent	Shallow
		Absent	Deep

The risk of wind damage is estimated as the probability of exceeding the critical wind speeds under the wind climate local to the stand (Hale et al., 2015). Therefore, information about the wind climate of a specific site is required for the calculation of the return periods of damaging wind storms. This is normally done using a Weibull distribution, either measured or derived (Seguro and Lambert, 2000). For this study, I have described the predominant westerly winds of Aquitaine with a value of 4.6 for the *A*-parameter (scale), and a value of 1.61 for the *k*-parameter (shape) of the Weibull distribution (Troen and Petersen, 1989). The cumulative probability of damage was calculated as the reciprocal of the return period of the critical wind speeds calculated by ForestGALES, with the probability of survival being defined as: (1 – probability of damage). For the 1st year of the rotation, the cumulative probability of survival is simply equal to the probability of survival. For each subsequent year, the cumulative probability of survival is calculated as the product of that year's probability of survival and the cumulative probability of survival calculated for the previous year. Finally, the cumulative probability of damage is trivially calculated for each year as: (1 – cumulative probability of survival).

4.2.6 Evaluation of species differences

To evaluate statistically the significance of the differences between the CWS of the two species, I fitted a linear model of CWS and the stand level variables shown in Table 4.2, including *Species*. Because CWS is highly dependent on tree height, I added this variable to the linear model, which sizeably increased the fit of the model. Conversely, I did not include *dbh* in the model, as its very large correlation with tree height meant that by including it the model fit did not improve. I log-transformed CWS because of the non-linear relationship between CWS and tree height. Because I used a different growth model for each species, I nested the variable *Growth Rate* within *Species*. In addition to this, since the effect of *Rooting Depth* is different for the two species, I nested *Rooting Depth* within *Species* in a separate term of the linear model. The structure of the statistical model is therefore as follows:

$$\ln(CWS) \sim tree\ height + (Species\ /\ Growth\ Rate) + (Species\ /\ Rooting\ Depth) + Gap\ size.$$

However, the residual plots of the linear model suggested variance heteroscedasticity. Similarly, the residuals plots of the auto-correlation function (ACF) and of the partial auto-

correlation function (PACF) indicated that a relation existed between successive values of the model, suggesting an auto regression of order 2 (see Appendix B). To account for heteroscedasticity, I described the model's variance structure with a combination of different variances for different levels of the categorical variables in Table 4.2, together with different weights for the variance of the residuals with relation to the magnitude of the continuous variable *tree height* (Zuur et al., 2009). To this aim, I used the *varComb*, *varIdent*, and *varPower* functions of the *R* package *nlme* (Pinheiro et al., 2016). To account for auto correlation of the residuals, I calculated the values of the autoregressive parameters with the *arima* function included in the standard installation of *R* (R Core Team 2016), and used them to specify the correlation structure of the residuals using the *corARMA* function of the *R* package *nlme* (Galecki and Burzykowski, 2013). Using the *gls* function of the standard installation of *R*, I then re-fitted the linear model using a generalised least squares method, to which I applied the above adjustments to account for heteroscedasticity and correlation of the residuals. As a result, the fit of the model (measured with AIC) considerably improved. I used the *p*-values of the ratios of the estimates of the coefficients of the linear model and their standard errors to evaluate the statistical differences between species.

For the cumulative probabilities of damage, I tested for the significance of the differences between the levels of the categorical variables in Table 4.2 with Kolmogorov-Smirnov tests. The output of the test is the maximum distance between two cumulative probability curves: the larger the value, the larger the difference between the curves. I computed the *p*-values to determine the significance of the calculated distances. I have used the *ks.boot* function of the *R* package *Matching* (Sekhon, 2011) which performs a bootstrap version of the univariate Kolmogorov-Smirnov test. This approach ensured that the test could be performed in my case of the distributions not being entirely continuous.

Finally, I plotted the calculated CWS and CPD for all the combinations of the variables shown in Table 4.2 against tree height, age, and stand yield, so as to identify critical values of these variables to compare the two species and to provide suggestions with regards to their silvicultural management.

4.3 Results

The results of the linear model show that the differences in CWS between *P. pinaster* and *E. globulus* are highly significant (*p*-value < 0.001). As expected, the effects of *tree height* and *Gap size* are highly significant (*p*-values < 0.001). The effect of *Growth Rate* is significant for both species, but more significantly for *E. globulus* (*p*-value < 0.001) than for *P. pinaster* (*p*-value < 0.05). The differences in CWS for different rooting depths are highly significant for *P. pinaster* (*p*-value < 0.001), and not significant for *E. globulus* (*p*-value > 0.9).

The results of the Kolmogorov-Smirnov tests for the differences between the cumulative probabilities of damage for the two species are shown in Table 4.3. The results mostly reflect those for CWS, in that the two species differ considerably, and the size of an upwind gap has a sizeable effect on CPD, especially for *E. globulus*. The CPD curves for *P. pinaster* differ for the two yield classes, while those of *E. globulus* do not for the two SI_{10} used in my simulations.

Table 4.3 - Results of the Kolmogorov-Smirnov test for difference between cumulative probability of damage curves for *P. pinaster* and *E. globulus*

Variables	Distance between CPD curves	*p*-value
Overall results:		
Species	0.28	****
Rooting Depth	0.12	*
Growth Rate	0.12	*
Gap size	0.25	****
Species - specific results:		
P. pinaster		
Rooting Depth	0.16	**
Growth Rate	0.13	*
Gap size	0.19	***
E. globulus		
Rooting Depth	0.02	1
Growth Rate	0.21	0.1
Gap size	0.42	****
CPD: Cumulative Probability of Damage		
***p*-value significance: (*) <0.05; (**) <0.01; (***) <0.005; (****) <0.001**		

Figure 4.1 shows the graphs of the calculated CWS for all the combinations of the variables shown in Table 2 against tree height, age, and stand yield.

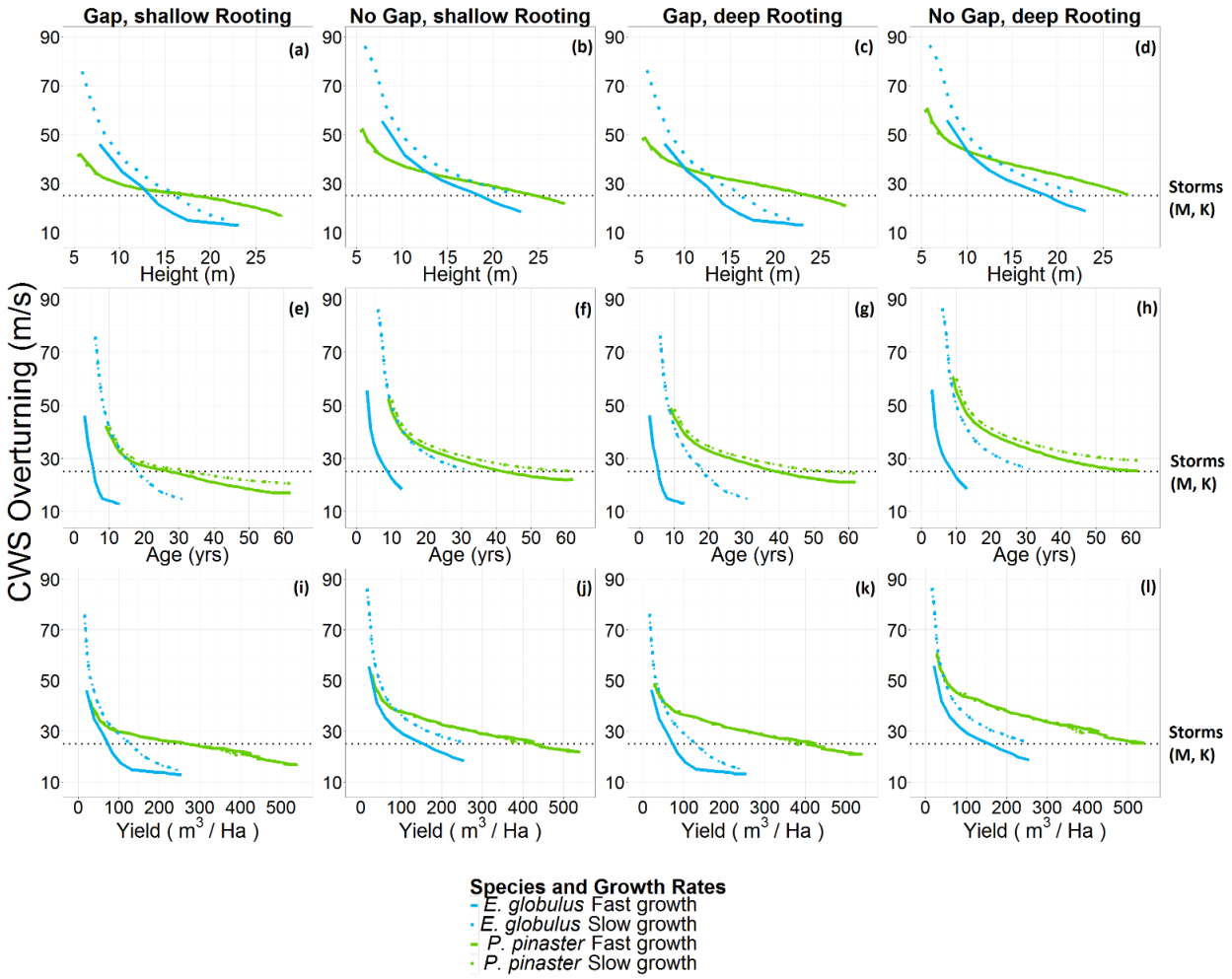


Figure 4.1 - : Critical wind speeds response to tree height, stand age and yield under fast and slow growths, shallow and deep rooting, and presence and absence of a windward gap. Storms (M, K) indicates the maximum hourly mean wind speeds of the storms Martin (1999) and Klaus (2009), as recorded inland. Note: in the Height plots (*a* to *d*) and Yield plots (*i* to *l*), the *P. pinaster* slow growth curve (dotted green) are not clearly visible because they overlap with the fast growth *P. pinaster* curves.

As seen in Figure 4.1 (graphs *a*, *b*, *c*, and *d*), critical wind speeds for overturning are lower (i.e. trees are more at risk) for *P. pinaster* than *E. globulus* until a height of about 10 - 13m for the fast growth scenario, and 13 – 19m for slow growth. I call this intersection point the "species threshold". Under slow growth conditions, and without an upwind gap, the two species behave similarly after this threshold. For all the other factors combinations, after this threshold the CWS curve for *E. globulus* decreases sensibly faster than for *P. pinaster*. Under fast growth, the presence of a gap seems to particularly affect *E. globulus*, as the simulated stand reaches the maximum mean hourly wind speeds from storms Martin and Klaus at around 14m in the presence of a gap, as opposed to approximately 18m without one. The *P. pinaster* curves level off after a sharp decrease, approaching the two storms' wind speeds almost asymptotically. This trait is common to all the CWS plots, regardless of the explanatory variable, but more marked for fast growth rates and in the presence of a gap.

Graphs *e*, *f*, *g*, and *h* in Figure 4.1 show the relationship between stands age and critical wind speeds. Note that for *P. pinaster* I do not have any values for trees younger than 9 years, due to the height lower bound of 5m for the ForestGALES simulations. For fast growth rates, CWS are lower for *E. globulus* than *P. pinaster*. For slow growth, until ~15 years of age the two species' CWS curves are similar in the presence of a gap. Without a gap, the CWS curves of the two species for slow growth shift upwards and are similar when shallow rooted, while those of *E. globulus* are lower when the trees are deeply rooted. As shown in the previous section, rooting depth particularly affects *P. pinaster*. After the species threshold, the CWS for *E. globulus* are always lower than *P. pinaster*'s. For fast growth, *E. globulus* CWS curve reaches the storms' maximum mean hourly wind speeds around 7 years with a gap, and ~9 years without one (graphs *e* and *g*, and *f* and *h*, respectively). In the presence of a gap *P. pinaster*'s CWS reaches the storms' wind speeds at ~25 years and ~32 years when shallow and deeply rooted, respectively (graphs *e* and *g*). For slow growth, with an upwind gap *P. pinaster* reaches CWS as low as the storms' maximum mean hourly wind speeds at ~27 years and ~38 years when shallow rooted (graphs *e* and *g*), while without a gap it does so at ~57 years when shallow rooted, and never when deeply rooted (graphs *f* and *h*, respectively). Slow-growing *E. globulus* reaches the storms' wind speeds at ~18 years into the rotation in the presence of a gap, regardless of the rooting depth, and ~30 years in the absence of a gap. As shown in Figure 4.1, graphs *i*, *j*, *k*, and *l*, under the fast growth rate scenario, the two species' responses are very similar until the volume per hectare has reached ~50 m^3 ha^{-1}. Above this threshold, critical wind speeds are lower for *E. globulus*, which reaches the wind

speeds during storms Martin and Klaus at ~90 m^3 ha^{-1} and ~150 m^3 ha^{-1} with and without a gap, respectively, and regardless of rooting depth (e.g. graphs *i* and *j*). With an upwind gap, *P. pinaster*'s critical wind speeds reach the storms' wind speeds at ~220 m^3 ha^{-1} and ~ 340 m^3 ha^{-1} for shallow and deep rooting, respectively (graphs *i* and *k*). Without a gap, it does so at ~400 m^3 ha^{-1} and ~460 m^3 ha^{-1} for shallow and deep rooting (graphs *j* and *l*). Under slow growth rates, CWS are lower for *P. pinaster* until a yield of ~100 m^3 ha^{-1}, after which the trend is reversed, as the *P. pinaster* CWS curves level off. Under this growth scenario, *P. pinaster* reaches the storms' wind speeds at the same yields as with fast growth rates, while *E. globulus* only does so in the presence of a gap, at ~140 m^3 ha^{-1} (graphs *i* and *k*).

Figure 4.2 shows the relationships between cumulative probability of damage and the three continuous variables (height, age, and yield) for fast and slow growth rates, shallow and deep rooting depths, and presence/absence of an upwind gap.

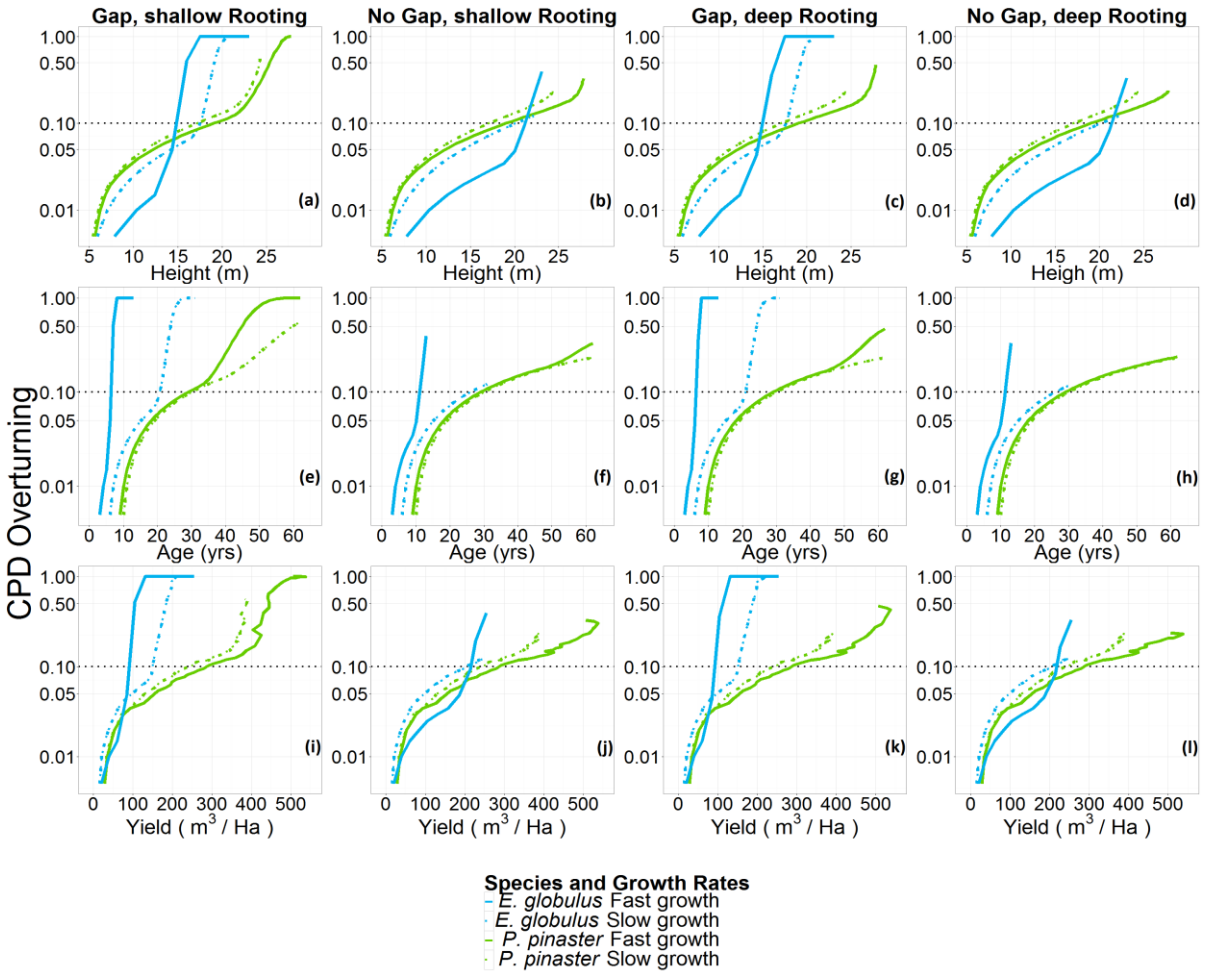


Figure 4.2 - Increase of cumulative probability of damage in response to tree height, stand age and yield under fast and slow growths, shallow and deep rooting, and presence and absence of a windward gap. Note: in the Age plots (e to h), the P. pinaster slow growth curves (dotted green) are not clearly visible because they partially overlap with the *P. pinaster* fast growth curves.

The graphs for cumulative probability of damage vs tree height (Figure 4.2, graphs *a*, *b*, *c*, and *d*) reflect those for the critical wind speeds. For fast growth rates, *E. globulus* curves for CPD lie below *P. pinaster*'s until they intersect at ~15m and 0.10 CPD with a gap, and at ~21m and ~0.20 CPD without. For slow growth rates, in the presence of a gap the two curves intercept at ~17m and ~0.20 CPD. Without a gap the two curves never intercept, with *E. globulus* remaining lower than *P. pinaster* and reaching 0.10 CPD at ~20m, as opposed to *P. pinaster*'s curve which reaches the same value of CPD at ~14m.

As shown in Figure 4.2, graphs *e*, *f*, *g*, and *h*, for fast growth rates, the CPD curves of the two species are very similar until ~5 years in the presence of a gap, and ~9 years without one. *E. globulus* reaches CPD=0.10 at ~6 years with a gap, as opposed to ~10 years without. *P. pinaster* reaches the same value of CPD at ~25 years regardless of gap. For slow growth rates, without a gap the two species behave very similarly, reaching CPD=0.10 at ~25 years. With a gap, their curves divert at ~18 – 19 years, corresponding to a CPD of 0.09, when *E. globulus* dramatically increases to CPD=1 within a period of ~10 years, while *P. pinaster* never does.

Graphs *i*, *j*, *k*, and *l* in Figure 4.2 show that, for fast growth rates and in the presence of a gap, *E. globulus*' CPD curve lies below *P. pinaster*'s until ~80m^3 ha^{-1} (CPD ~0.06), after which it quickly increases to CPD=1, passing at CPD=0.10 at ~90m^3 ha^{-1}, while *P. pinaster* reaches CPD=0.10 at ~200m^3 ha^{-1}. Without a gap, the two curves intercept at CPD ~0.10, corresponding to ~200m^3 ha^{-1}. For slow growth rates and the presence of a gap, the two curves are similar until CPD ~0.10 (for Vol/Ha ~140m^3 ha^{-1}), past which *E. globulus* CPD values quickly rise towards a value of 1. Without a gap the two species are very similar, reaching CPD=0.10 at ~160m^3 ha^{-1}.

4.4 Discussion

In this Chapter I have compared the resistance to wind damage of *P. pinaster* and *E. globulus*, two commercial species extensively planted in south-western Europe for pulp, timber, and biomass production for energy. This study originated because of the differences in reported damage to *P. pinaster* plantations in France following storms Martin (1999) and Klaus (2009), which was extensive, and *E. globulus* plantations in France and the Iberian Peninsula, where reported damage was scarce. I have used computer simulations to mimic conditions typical of the Aquitaine region in France with the wind-risk model ForestGALES. I have investigated the effect on wind resistance of a large upwind gap, of two different rooting depths (shallow

and deep, due to the presence of a discontinuous hardpan layer typical of the soils in the area (e.g. Khuder et al., 2007)), and of two growth rates common in the region for *P. pinaster* and for two other Eucalypt species planted in France.

Juvenile *E. globulus* trees are at lower risk of wind damage than *P. pinaster* trees of the same age, while as the trees age and grow taller the situation is reversed. These trends are less marked under the fast growth scenario and in the absence of a windward gap, where the differences between the two species are less evident. This is likely attributable to the faster growth rates of *E. globulus* relative to *P. pinaster* under both growth rate scenarios (e.g. Kardell et al., 1986; Moreaux et al., 2013), as well as to the well-known influence of a windward gap in reducing the critical wind speeds (CWS), regardless of tree species (Somerville, 1989; Ruel et al., 2000; Peltola, 2006; Gardiner et al., 2008; Locatelli et al., 2016). Above the "species threshold", *P. pinaster*'s CWS curves decrease very gently as the continuous variables increase, while *E. globulus*' curves continue dropping quite steeply, regardless of growth rate, before levelling off when already below the wind speeds recorded for the destructive storms of 1999 and 2009. This age-related difference between the two species suggests that, especially under fast growth scenarios, forest managers in Aquitaine should either opt for short *E. globulus* rotations, or for conventional *P. pinaster* management.

Both gap and growth rates have large effects on how the two species respond in terms of the calculated CWS. Without a windward gap, the *P. pinaster*'s CWS curves only reach CWS as low as storms Martin and Klaus rather late in their rotation. However, this species' curves remain very close to such CWS values for extended ranges of tree height, age, and yield, as they are almost asymptotical to the horizontal line corresponding to the maximum mean wind speed in storms Martin and Klaus. This is likely attributable to the reduced growth rates late in the rotations, as described by Trichet et al. (2009) in their long-term study on *P. pinaster*'s growth response to soil fertilisation in Aquitaine. In my simulations, under the slow growth scenario both species are relatively safe from previous forest-damaging wind speeds for most of their rotation, especially without a windward gap. This finding suggests that under suboptimal growth conditions both species' rotations can be extended without the stands being exposed to historically damaging wind speeds. This has important practical implications as it reduces the harvesting frequency required to maintain the stands wind-risk free. While both species are associated with lower CWS, *ceteris paribus*, under the fast growth scenarios,

they respond differently to the difference in growth rates, *E. globulus* being more sensitive than *P. pinaster*. This is especially visible in the age plots (Figure 4.1, graphs e, f, g, and h). In terms of timber yield, for fast growth rotations and in presence of a gap, *P. pinaster* reaches the maximum mean hourly wind speed recorded during the Martin and Klaus storms (~25 m s^{-1}) with a yield about two to three times as large as for *E. globulus*, regardless of rooting depth (shallow rooting: *P. pinaster* ~220 m^3 ha^{-1} and *E. globulus* ~90 m^3 ha^{-1}; deep rooting: *P. pinaster* ~400 m^3 ha^{-1} and *E. globulus* ~170 m^3 ha^{-1}), as shown in graphs i and k of Figure 4.1.

My study shows that rooting depth does not affect *E. globulus*' CWS, while it does have a marginal effect on *P. pinaster* in the juvenile stages of the rotations, as it can be seen in all the CWS plots (Figure 4.1). This could be attributable to my inability to model the effective rooting depths of the two species using the depth of a hardpan layer as a proxy for the trees' rooting depths. This is particularly likely to be the case for *E. globulus*, for which a comprehensive exploration of the role of rooting depth on resistance to pulling was not possible at the time of the tree-pulling experiments, as discussed in Chapter 3. In fact, I have shown that in my fieldwork the differences in the anchorage of *E. globulus* with and without a tap-root, used in this Chapter to simulate the absence and presence of a hardpan layer, respectively, were minimal. Despite this caveat, this finding is in agreement with the findings of Cucchi et al. (2005), Danjon et al. (2005), and Khuder et al. (2007), whose experimental studies concluded that deep-rooted *P. pinaster* trees in Aquitaine are more wind-firm than shallow-rooted ones. Similarly to the study of Cucchi et al. (2005), in my study I used the presence or absence of a hardpan layer to simulate two rooting depths, and variation in other soil characteristics is not modelled in my simulations. For instance, I did not model the intense rainfall commonly associated with strong winds (Liberato et al., 2010), which would result in waterlogged soils, especially when a hardpan is present, and may affect tree anchorage. This point is particularly relevant since almost half (44%) of the soils in Aquitaine are classified as humid moorland (Trichet et al., 2009). In contrast, the extensive water use of Eucalypt trees might significantly reduce soil water content and might improve tree anchorage, especially on poorly drained soils with a hardpan. Moreaux et al. (2013) have indeed shown that Eucalypt trees are able to respond very quickly to rainfall events by rapidly increasing their stem diameter. Important considerations should be taken into account in regards to the IPCC's projected changes in the local Aquitaine climate, especially with regards to winter temperatures and summer droughts, to which Eucalypt species are known to be

particularly sensitive. While some of the *Eucalyptus* spp. planted in France do perform well under water stress and winter frosts, my assumption that their resistance to wind damage is comparable to *E. globulus*' needs also to be investigated with further tree-pulling tests.
It is interesting to note that for certain factor combinations (gap x rooting depth x growth rate), *P. pinaster*'s simulated CWS never reach the maximum hourly mean wind speeds recorded for the Klaus and Martin storms, or only do so at the very end of their rotation. However, massive *P. pinaster* timber losses were recorded in Aquitaine for both storms (e.g. Cucchi et al., 2003; Costa et al., 2009). This could be due to the fact that wind speeds measured inland were likely higher in many parts of the forests in Aquitaine. An alternative explanation is that brief, strong gusts of wind, likely responsible for these large losses, were potentially not recorded during the storms due to their short duration. Kamimura et al. (2016) argue that the constant harvesting of nearby sites prevents trees in Aquitaine from becoming fully acclimated to wind, and frequently exposes stands to newly formed upwind gaps. In light of these considerations, forest managers might choose to adopt shorter rotations, whose length can be determined by investigating the Cumulative Probability of Damage (CPD) curves rather than those for CWS.

Overall, my simulations show that and intraspecific differences between *P. pinaster* and *E. globulus*, and the presence/absence of a recently created upwind gap, are the most important drivers of cumulative risk, while rooting depth and growth rates are only important for *P. pinaster*. In my simulations *E. globulus* generally performs better in terms of CPD than *P. pinaster* until a height of about 14 – 20 m. This is especially true for the scenarios without a windward gap and under fast-growing rotations (SI_{10}=10 vs YC=4 for *E. globulus* and *P. pinaster*, respectively). For slow growth rates and without a gap, *E. globulus* is associated with lower CPD values than *P. pinaster* regardless of tree height. The effect of an upwind gap is particularly evident for fast growth rates and more markedly for *E. globulus*, which without an upwind gap reaches CPD=0.10 for trees significantly taller (~20m as opposed to ~15m) than *P. pinaster*. For slow growth rates, this trend is confirmed regardless of the presence of a windward gap. As noted above, while the value of YC=4 is representative of the slow growth rate of *P. pinaster* in Aquitaine, the low value of SI_{10} for *E. globulus* (i.e. 10) is likely to be quite conservative and hence perhaps not representative of the potential growth rate of Eucalypts in the area (Moreaux et al., 2013). In light of these considerations, forest managers choosing to adopt *E. globulus* for their commercial plantations should take great care in ensuring that

formation of new edges is avoided when possible. It should be noted that I have based my simulations on the practice, common in Aquitaine, of frequent harvests of adjacent stands (Kamimura et al., 2016), which results in an almost constant exposure of a planted stand to newly created gaps. Under this assumption, my simulated stands exposed to an upwind gap are never allowed to acclimate to the increasing wind loading resulting from the presence of an upwind gap. In this sense, my calculated CPD could be overestimated.

When comparing the two species in terms of stand age, my simulations show that, for slow growth rates and without a gap, *P. pinaster* and *E. globulus* perform quite similarly, reaching CPD=0.10 at approximately 20 years. Under slow growth rates and without a gap, *E. globulus* performs slightly worse than *P. pinaster*. For fast growth rates, *E. globulus* reaches this threshold at a much younger age (~5 to 7 years) than *P. pinaster* (~25 years), especially in the presence of a gap. These findings again suggest the use of much shorter rotations for *E. globulus* than *P. pinaster* in Aquitaine to reduce the risk of wind damage, should optimal growth rates be achieved. However, given the faster growth rates of *E. globulus* and *Eucalyptus* spp. in general (Neilan and Thompson, 2008; Leslie et al., 2012; Moreaux et al., 2013), it should be possible to achieve cumulative larger yields than with *P. pinaster* under shorter rotations without exceeding CPD values of 0.10. That is, while the yield from a single rotation of *E. globulus* is lower than that of *P. pinaster*, the rotation length of the former is much shorter. Therefore, over the same time period, *E. globulus* can produce higher yields overall. While my simulations show that for SI_{10}=20 and YC=2 in the presence of an upwind gap *E. globulus* performs particularly badly relatively to *P. pinaster* in terms of the relationship between yield and CPD, without a gap the two species both reach CPD=0.10 at a yield of ~200 m^3 ha^{-1}. This suggests that an *E. globulus* rotation of about 10 years would be sufficient to produce a yield equivalent to a *P. pinaster* rotation of about 20 – 25 years, for the same CPD value at harvest time. It is also important to note that, according to my simulations (for this scenario), until the "species threshold" (which corresponds to CPD$\simeq$0.10 for fast growth and no gap, and slow growth with a gap) *E. globulus* is exposed to significantly lower CPD values almost until this threshold, especially when comparing SI_{10}=20 and YC=2 without an upwind gap. This finding, if confirmed experimentally, would significantly strengthen the case for the better suitability of *E. globulus* in terms of wind damage risk in Aquitaine.

In terms of yields, under the slow growth scenario the two species behave quite similarly until CPD=0.10, with *P. pinaster* performing marginally better. Past this CPD value, the influence of gap becomes prominent, and more markedly for *E. globulus*. In the presence of a gap *P. pinaster*'s CPD grows very gently until large yields are achieved (~350 m^3 ha^{-1}), while *E. globulus*' rapidly increases towards CPD=1. The effect of gap on both species is demonstrated by the slow growth – no gap scenario, where both species' CPD increase very slowly until their maximum simulated yields without ever reaching CPD=0.50. It is also interesting to note that, based on my simulations, the common rotation length of *P. pinaster* in Aquitaine (>35 years, Trichet et al., 2009) already falls within an area of CPD values larger than 0.20 (i.e. more than 1 in 5 chance of damage) for all the combinations of my factors (growth rate, gap, rooting depth). In the event of a large wind-induced loss, the fast growth rates and short rotation lengths of *E. globulus* would allow for a quick recovery of the losses with the subsequent rotation, while this would not be possible for *P. pinaster*.

In light of my findings, I attempt to advance some possible explanations for the low levels of wind damage to *Eucalyptus* stands in northern Spain and Portugal following storm Klaus. As shown by Liberato et al (2010) the northern parts of the two countries, where both *P. pinaster* and *E. globulus* are grown, recorded similar wind speeds to those in Aquitaine. However, the damage to *P. pinaster* plantations in Aquitaine was catastrophic, while wind damage to *E. globulus* in Portugal and Spain was substantially less (Riera, 2011; Trabado, 2009).

Eucalypts in northern Spain are protected topographically from a westerly, since the coast is to the north, while *P. pinaster* trees in Aquitaine were totally unprotected. Indeed, in northern Spain and Portugal any ridge or hill to the west has the ability to reduce the wind exposure on trees. Despite the findings reported in Chapter 3 about the low importance of the soil/rooting system in Eucalyptus' resistance to overturning, it can be argued that the different soils in Spain and Portugal might provide Eucalyptus trees with better anchorage than the soils with an ironpan in Aquitaine. Indeed, the tree-pulling tests reported in Chapter 3 were limited to only one location, where the soil was homogeneous, and no tree pulling of *Eucalyptus* spp. has been performed on soils typical of Aquitaine. An alternative explanation might be related to *E. globulus* rotation lengths in Portugal and northern Spain. Since Portuguese Eucalypts are harvested at a young age (Águas et al., 2014), which as I have

shown is associated with low CPD and high CWS, they might have not been vulnerable to the wind speeds recorded during storm Klaus.

4.5 Conclusions

My simulations for the Aquitaine region in south-western France suggest that in this area *E. globulus* compares favourably with *P. pinaster* with regards to wind damage, indicating that Eucalypt species have the potential to be figured more prominently in the Aquitaine region, where the currently predominating species is *P. pinaster*. This is under the assumption that commercial Eucalypt species that able to withstand the occasional harsh winter frosts in the region, such as *E. nitens*, *E. gunnii*, *E. dalrympleana*, and *E. gundal* (a hybrid of the latter two), share similar mechanical timber and rooting properties with *E. globulus*. The principal reasons for the suitability of Eucalypt species in the area are their very high productivity and short rotation lengths, which allow for shorter rotations than *P. pinaster* while providing high yields. In light of this, not only shorter rotations mean that the standing timber is exposed to lower cumulative risk throughout the trees' growing period, but also that in the event of a destructive storm the losses incurred can be offset in a shorter period than for species which grow more slowly, such as *P. pinaster*. Ultimately, choosing a tree species over another is a complex task, as it depends on the desired goals and the acceptable level of risk set by the forest manager, as well as on the environmental (i.e. soil quality, presence or scheduling of neighbouring upwind harvests) and growing conditions in the area of interest. For these reasons, mechanistic models such as ForestGALES, that can efficiently simulate different environmental conditions and forest management options, are an invaluable tool in aiding forest managers to evaluate viable options for their forests with regards to the risk of wind damage.

Chapter 5 Comprehensive global sensitivity analysis of ForestGALES

5.1 Introduction

Environmental modelling has become a crucial part of the study of environmental phenomena. Significant advances in the fields of hardware and computing now allow for the creation of complex, computationally-demanding, process-based models, aimed at the investigation of natural systems (e.g. Nossent el al., 2011). These complex models are extensively adopted in support of decision-making and for environmental policy settings (e.g. Rahmstorf et al. (2007) on IPCC projections). While a large amount of time and resources are spent to formalise nature in mathematical terms, considerably less effort is often made to investigate the behaviour of mathematical models, which is often done as an "afterthought" (Saltelli and Funtowicz, 2014). As elegantly discussed by Oreskes et al. (1994), the same practices of model validation, evaluation, and confirmation, are philosophical and practical minefields. Modellers are confronted with these issues for a number of reasons: natural systems, which are inherently open in nature, are forced into close systems to obtain mathematical solutions; scaling issues can arise when the scales at which some elements of a model are calculated differ from the scale of application of the model; nonuniqueness of modelling approaches might result in a faulty model providing "reasonable" outputs (Oreskes et al., 1994). Ultimately, however, the main issue with environmental modelling is the same reason why models are built: one can never exactly know all the data, and those that are known, are accompanied with a degree of uncertainty. Deterministic approaches to modelling require elimination of these uncertainties, thus effectively further removing a model from its intended representation of reality. The inadequacy of the attempts to eliminate at all costs the uncertainties of the parameters and variables of a model, in order to produce completely deterministic results, is nowadays generally accepted (e.g. Penman et al., 2003). The transparency of model predictions is an important requirement especially when models are applied for decision-making, and in policy frameworks (e.g. the US Environmental Protection Agency, see Gaber et al. (2009)). To this end, uncertainty analysis is normally applied to quantify the uncertainties of the input variables, parameters, and outputs of a model, thus providing some insight on the reliability and the applicability range of the model.

On the other hand, the issue of sensitivity of model predictions to variation in model parameters and variables is still relatively underestimated. However, when performed appropriately (Saltelli and Annoni, 2010), sensitivity analysis (SA) of mathematical models is a tool that can help with fundamental issues about the robustness and the behaviour of a model (Tarantola et al., 2002). A number of techniques exist to perform sensitivity analysis, as discussed in Chapter 2. Of these variance-based GSA techniques, the method of Sobol' has found favour with modellers in the environmental sciences, because of the relatively straightforward interpretation of the sensitivity indices calculated with this method, and because it very efficiently samples the factors space (Sobol', 1990; Yang, 2011; Kucherenko et al., 2015). The Sobol' method is often used as a benchmark against which to compare the results of other SA techniques (Confalonieri et al., 2010). Nossent et al. (2011) successfully applied the Sobol' method to the identification of the most, and the least, important factors in a SWAT model (Soil and Water Assessment Tool). The authors also provided an exhaustive description of the Monte Carlo procedures required for the calculation of the Sobol' sensitivity indices. Song et al. (2012) used the method of Sobol' for the SA of the 3-PG2 forest growth model, aimed at model calibration. A known issue with variance-based GSA techniques is how to account for correlation between factors when calculating the conditional variances. Indeed, correlation amongst factors in environmental models is typical. A number of studies propose methods to obviate the issue of dependent factors in GSA (e.g. Mara and Tarantola, 2012; Most, 2012).

In this Chapter, I submit ForestGALES to a comprehensive variance-based GSA using the method of Kucherenko et al. (2012), a generalisation of the method of Sobol' for correlated factors. The rationale of ForestGALES, together with the most important model calculations for the context of my GSA, is discussed in the Methods section of this thesis. For a thorough description of the model, the interested reader is referred to Hale et al. (2015). Variance-based GSA are normally applied to complex models composed of a large number of factors, sometimes in excess of one hundred, mostly for the direct benefit of the modelling community. In this Chapter, I limit my GSA to the inputs of ForestGALES that are controllable by the end-users. Focussing on those input variables that are user-modifiable extends the benefits of a GSA to the end-user base of an environmental model, and facilitates the interpretation of the results of the SA in a practical setting. To extend the results of my GSA to a large user-base community, I perform my GSA on three species *(Picea sitchensis* (Bong.) Carr., *Pinus pinaster* (Ait.), and *Eucalyptus globulus* (Labill.)),

representative of three of the most extensively planted and highly productive tree genera worldwide: spruces, pines, and eucalypts.

Besides extending the sensitivity analysis to *P. sitchensis* and *P. pinaster*, the main differences between the sensitivity analysis presented in Chapter 3 and that presented in this Chapter pertain to the role of Rooting Depth and Soil Type, and the nature of an upwind Gap. In fact, in Chapter 3 Rooting Depth and Soil Type were not included in the analysis, due to the fact that the fieldwork for the parameterisation of ForestGALES for *E. globulus* was performed on a site with a homogeneous soil type, and that the differences in the C_{reg} values between trees with and without a tap-root (a proxy for Rooting Depth) were minimal. In Chapter 3, a gap was assumed to be newly formed (i.e. corresponding to a brown edge), while in this Chapter gap is assumed to be associated with a green edge (i.e. a pre-existing gap). In this Chapter I also investigate the differences in the ranking of the influential variables between the three species, to evaluate whether the sensitivity of the model is the same across the species used in the simulations.

In this Chapter I focus my attention on two questions that SA can help with: (1) What model inputs should a user of ForestGALES focus on knowing more accurately to maximally reduce the uncertainty in the model predictions? (2) What model inputs contribute the least to the variation in the output? The first question can be answered under the Factor Prioritisation setting of GSA, while the second pertains to the Factor Fixing setting (Saltelli et al., 2008). Both settings are discussed in the Methods section of this thesis.

5.2 Materials and methods

5.2.1 The ForestGALES model

ForestGALES is described in depth in Chapter 2 of this thesis. For the purpose of this Chapter, I draw the attention of the reader to the diagram shown in Figure 2.1, where the rationale and the architecture of ForestGALES are depicted with a focus on the interaction between the input variables. The diagram in Figure 2.1 shows that ForestGALES is composed of two main modules: the first one, often referred to simply as GALES (Gardiner et al., 2000), makes use of tree and stand variables to calculate the CWS for breakage and overturning (henceforth: $CWS_{(B, O)}$). In GALES, tree height and dbh are featured in the

calculations of canopy dimensions and aerodynamic properties, as well as being involved in the calculations of the mean wind profile, together with sph and size of an upwind gap. Soil type and rooting depth are used in species-specific sub-modules to retrieve the values of species-specific coefficients (C_{reg}) of linear regressions of total overturning moment, as measured empirically in the field, against stem weight under different soil types and rooting depths. These relationships are derived from tree-pulling fieldwork data used in species parameterisations of ForestGALES (see Nicoll et al. (2006) for *P. sitchensis*; Cucchi et al. (2005) for *P. pinaster*; and Chapter 3 (Locatelli et al., 2016) for *E. globulus*). For *E. globulus*, only one value is available because tree-pulling was performed only in one location with homogeneous soil type (162.32 N m kg^{-1}, as discussed in Chapter 3). The values of C_{reg} for *P. sitchensis* and *P. pinaster* are shown in Table 5.1.

Table 5.1 - Values of the linear regressions of total overturning moment vs stem weight, for combinations of rooting depth (shallow, medium, and deep) and soil type (freely draining, gleys, mineral peats, and deep peats). *P. sitchensis* and *P. pinaster* are shown here. Only one value available for *E. globulus* (162.3, from Chapter 3). Units are N m kg^{-1}. s.d. denotes the standard deviation.

Picea sitchensis		Rooting depth				
		Shallow	**Medium**	**Deep**	**Soil Average**	**Soil s.d.**
Soil Type	**Freely draining**	153.2	156.2	178.1	162.5	13.6
	Gleys	135.4	138.5	157.9	143.9	12.2
	Mineral peats	147.8	151.2	172.5	157.2	13.4
	Deep peats	168.1	172.1	196.2	178.8	15.2
	Depth average	*151.1*	*154.5*	*176.2*		
	Depth s.d.	*13.5*	*13.9*	*15.8*		

Pinus pinaster		Rooting depth				
		Shallow	**Medium**	**Deep**	**Soil Average**	**Soil s.d.**
Soil Type	**Freely draining**	125.8	168.8	144.5	146.4	21.6
	Gleys*	124.2	144.4	126.7	131.8	11.0
	Mineral peats*	135.6	157.7	138.3	143.9	12.1
	Deep peats*	154.3	179.4	157.3	163.7	13.7
	Depth average	*135.0*	*162.6*	*141.7*		
	Depth s.d.	*13.8*	*15.0*	*12.8*		

*C_{reg} values of soil types: gleys, mineral peats, deep peats for *P. pinaster* are taken from those of *P.sylvestris* (L.).

Soil type and rooting depth do not contribute to the calculation of CWS_B, and therefore for this output they are expected not to be flagged as important in the SA. The large number of interactions between input variables that can be seen in Figure 2.1 are summarised in the formulas for the calculation of CWS_B (Eq. 2.13) and CWS_O (Eq. 2.12). Table 5.2 shows the input variables involved in the calculations of the non-constant terms in these formulas.

Table 5.2 - Mapping between ForestGALES input variables and the non-constant terms of the formulas for the calculations of the critical wind speeds for breakage (CWS_B) and overturning (CWS_O). [a]Species is used as a trigger to select species-specific sub-modules; [b]Rooting depth and Soil type are involved in the calculations of d, f_{CW}, and z_0 only for CWS_O; [c]C_{reg} values are empirically derived (see Chapter 2 for a brief explanation, or Nicoll et al. (2006) for a complete description of tree-pulling fieldwork techniques). The symbol (✓) denotes which formula variables are present in the corresponding calculations of the critical wind speeds for breakage and overturning.

Formulas Variables		CWS_B	CWS_O	Input Variables[a]
D	Mean tree spacing	✓	✓	Sph
G	Gust Factor	✓	✓	Tree height; Sph; Gap Size
d	Zero-plane displacement	✓	✓	Tree height; Dbh; Sph; Gap Size; Rooting depth[b]; Soil type[b]
f_{CW}	Tree mass factor	✓	✓	Tree height; Dbh; Sph; Gap Size; Rooting depth[b]; Soil type[b]
h	Mean tree height	✓	✓	Tree height
z_0	Canopy roughness	✓	✓	Tree height; Dbh; Sph; Gap Size; Rooting depth[b]; Soil type[b]
C_{reg}[c]	Overturning moment multiplier		✓	Rooting depth; Soil type
SW	Stem weight		✓	Tree height; Dbh

In the second main module of ForestGALES (WCM, see Figure 2.1), the local wind climate is used to calculate the return period of a storm with maximum mean wind speeds that would match, or exceed, the calculated $CWS_{(B, O)}$. The probabilities of breakage and overturning (henceforth: $Prob_{(B, O)}$) are calculated as the inverse of the return period.

5.2.2 Procedure for the GSA of ForestGALES

An introduction to variance-based sensitivity analysis methods is presented in Chapter 2. Nossent et al. (2011) provide a thorough and accessible explanation of the theory and the mathematics adopted in the method of Sobol'. Here, I limit myself to briefly discussing the modifications contributed by Kucherenko et al. (2012) for the case of correlated inputs.

5.2.2.1 Generalisation of the Sobol' method for the case of correlated variables

In the case of correlated inputs, describing the inputs uncertainty with independent marginal distribution functions is inadequate. Kucherenko et al. (2012) suggest sampling from both the joint and conditional distribution functions of the inputs, which requires calculating the correlation matrix of the inputs. When at least one of the inputs is non-normally distributed, the authors suggest the use of a Gaussian copula, widely used in studies of financial risk (e.g. Cherubini et al., 2004). Adopting a Gaussian copula for SA allows for the use of a correlated multivariate normal distribution for the case of correlated variables. In this setting, correlated inputs are described by their marginal distribution and a measure of their correlation with the other inputs:

$$\boldsymbol{C}(\boldsymbol{G_1}(\boldsymbol{X_1}), \dots, \boldsymbol{G_n}(\boldsymbol{X_n});\ \boldsymbol{\Sigma_X}) = \boldsymbol{F_n}\left(\boldsymbol{F^{-1}}(\boldsymbol{G_1}(\boldsymbol{X_1})), \dots, \boldsymbol{F^{-1}}(\boldsymbol{G_n}(\boldsymbol{X_n}));\ \boldsymbol{\Sigma}\right) \quad \textbf{(5. 1)}$$

Where *C* denotes the copula; $G_{1\dots n}$ are the marginal univariate cumulative distribution functions; $X_{1\dots n}$ are the original inputs; Σ_X is the original correlation matrix; F_n is the multivariate cumulative *normal* distribution function; F^{-1} is the inverse normal cumulative distribution function; and Σ is the correlation matrix of the corresponding joint *normal* distribution function. With this approach, the original correlation matrix Σ_X of an original input vector $\boldsymbol{X}$ is mapped to the correlation matrix Σ. The adoption of copulas is convenient for SA because all the information on the dependencies between inputs is contained in the copula, while the information contained in the marginal distributions of the inputs is provided by the marginal univariate *cumulative* distribution functions of the inputs (Sklar, 1973). The sensitivity indices calculated with the method of Kucherenko et al. (2012) contain both the uncorrelated and the correlated part of the indices. In my study I used eq. 5.4 and 5.6 in Kucherenko et al. (2012) for the calculations of S_i and S^T_i, respectively, at a cost of $N(2m + 2)$ (35,200 in my case) model runs, using the Quasi-Monte Carlo method of Sobol' applied to the case of correlated variables (Sobol', 1990; Kucherenko et al., 2012). Quasi-Monte Carlo methods are commonly used in GSA because they provide enhanced convergence properties in comparison to traditional Monte Carlo methods, and hence require considerably less model executions (Sobol', 1998; Kucherenko et al., 2012).

5.2.2.2 Data used in the GSA of ForestGALES

Both the original method of Sobol' and that of Kucherenko et al. (2012) require knowledge of the probability distribution functions of the inputs for the generation of the samples. I described some variables (Sph, Rooting depth, Soil type, Gap size, and DAMS) with uniform or discrete uniform distributions, using the same distribution parameters for all the species, because I wanted to explore as large an input space as possible with regards to these variables. The gap used in this Chapter is what is normally referred to as "green edge gap"; that is, a gap that has been in place for some time, rather than a newly exposed one. For tree height and dbh, I fitted normal distributions to tree-pulling data for the three species used in this Chapter: for *P. sitchensis*, I used data from the UK Forestry Commission tree-pulling database; for *P. pinaster*, I combined tree-pulling data from Cucchi et al. (2005) with data from a similar species (Scots pine, *Pinus sylvestris* (L.)), from the UK database, because complete data for *P. pinaster* was not available. In fact, tree-characteristics between *P. pinaster* and *P.sylvestris* are very similar. For *E. globulus*, I used tree-pulling data presented in Chapter 3 for the parameterisation of ForestGALES. I imposed lower bounds to the distributions of tree height (4m) and dbh (3cm), to ensure that the functional limits of ForestGALES were not exceeded. The parameters of the inputs distributions are shown in Table 5.3.

Table 5.3 - Parameters of the probability distribution functions used for the generation of quasi-random samples used for the calculation of sensitivity indices. Dbh: diameter at breast height (1.3m); Sph: stems per hectare; DAMS: Detailed aspect method of scoring, a measure of the windiness of a site. [a]Lower bound for tree height: 4m. [b]Lower bound for dbh: 3cm.

Variable	Species	Parameters of the Normal Distribution	
		Mean	sd
Tree height[a] (m)	*Picea sitchensis*	13.64	2.64
Dbh[b] (cm)		19.89	4.52
Tree height[a] (m)	*Pinus pinaster*	13.70	2.75
Dbh[b] (cm)		18.98	3.51
Tree height[a] (m)	*Eucalyptus globulus*	23.17	4.59
Dbh[b] (cm)		21.78	7.51
	Type of distribution	**Min**	**Max**
Sph	Discrete Uniform	300	3300
Rooting depth	Discrete Uniform	1	3
Soil type	Discrete Uniform	1	4
Gap size (m)	Uniform	0	1000
DAMS	Discrete Uniform	7	22

I calculated the correlation matrix (Σ_X) of the input variables for the three species for the Gaussian copula required for the GSA, shown in Table 5.4. For all the species, the most relevant correlation was between tree height and dbh (*P. sitchensis*: 0.54; *P. pinaster*: 0.72; *E. globulus*: 0.91. All *p*-values < 0.001). I calculated the correlation between these two variables from species-specific data. Due to the fact that correlation data involving the other variables were only available for *P. sitchensis*, I have applied this to all the species. Gap size and DAMS are not correlated to any other variable. The large values of the Pearson correlation coefficients between tree height and dbh justify the use of the GSA method for correlated variables.

Table 5.4 - Correlation matrices for ForestGALES input variables for *P. sitchensis*, *P. pinaster*, and *E. globulus*. Dbh: diameter at breast height; Sph: stems per hectare; Gap size and DAMS are not shown because uncorrelated to the other variables. Correlations involving the following variables: Sph, Rooting depth, and Soil type, are calculated on *P. sitchensis* data from the UK Forestry Commission's tree-pulling database, and applied to the other two species. For this, the correlations between these variables are the same for all species. [a] The significance of the correlation between pairs of variables with Pearson's correlation coefficient > 0.3 (thus retained in the calculation of the copula) is large (all *p*-values < 0.001).

Picea sitchensis	**Height**	**Dbh**	**Sph**	**Rooting depth**	**Soil type**
Height	**1**	0.54[a]	-0.07	0.22	-0.07
Dbh		**1**	0.04	0.13	-0.02
Sph			**1**	0	-0.28
Rooting depth				**1**	-0.35[a]
Soil type					**1**

Pinus pinaster	**Height**	**Dbh**	**Sph**	**Rooting depth**	**Soil type**
Height	**1**	0.73[a]	-0.07	0.22	-0.07
Dbh		**1**	0.04	0.13	-0.02
Sph			**1**	0	-0.28
Rooting depth				**1**	-0.35[a]
Soil type					**1**

Eucalyptus globulus	**Height**	**Dbh**	**Sph**	**Rooting depth**	**Soil type**
Height	**1**	0.91[a]	-0.07	0.22	-0.07
Dbh		**1**	0.04	0.13	-0.02
Sph			**1**	0	-0.28
Rooting depth				**1**	-0.35[a]
Soil type					**1**

In Figure 5.1 I show the effect of the correlation between Rooting depth and Soil type (Pearson correlation coefficient: -0.35; *p*-value < 0.001) on the sampling matrix calculated with the copula method. The occurrence of the different Soil types modelled in Figure 5.1 is

representative of the *P. sitchensis* tree-pulling database used for the calculation of the correlation coefficients.

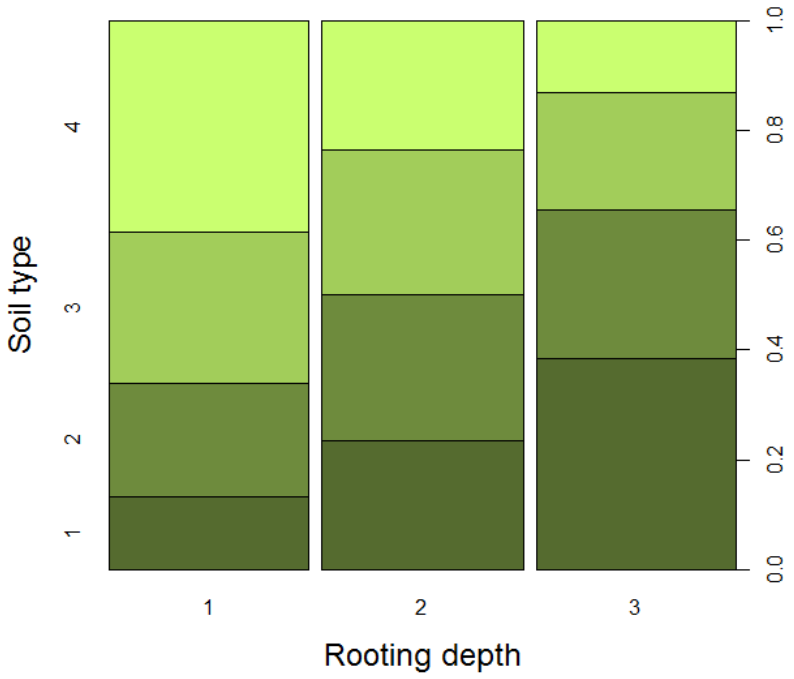


Figure 5.1 - Distribution of the levels of Rooting depth and Soil type in the generation of the sample for the sensitivity analysis using the copula method. The Pearson correlation coefficient between the two variables is -0.35. Rooting depth levels: 1=shallow; 2=medium; 3=deep. Soil type levels: 1=Freely draining; 2=Gleys; 3=Mineral peats; 4=Deep peats. This Figure shows that the Quasi-random values of Rooting depth and Soil type generated with the method of Sobol' are influenced by the correlation structure of the copula. E.g.: for shallow Rooting depth (level: 1), the likelihood of a Soil type "Deep peats" (level: 4) is higher than that the other types of soil. For deep Rooting depth (level: 3), the likelihood of a Soil type "Freely draining" (level: 1) is higher than that of the other types of soil. For medium Rooting depth (level: 2) all Soil types are almost equally likely to be selected with the Quasi-random number generator under the correlation structure of the copula.

5.2.2.3 ForestGALES simulations

From the samples generated for each of the three species, I used ForestGALES to calculate two sets of outputs, $CWS_{(B, O)}$ and $Prob_{(B, O)}$. Because of the structure of the model, and the nature of the outputs, I performed different analyses on the two sets of outputs, as described below.

5.2.2.3.1 Critical wind speeds

In order to investigate what variables the model users should focus on knowing more accurately to maximise the reduction in the uncertainty of the model's predictions of CWS, I applied the SA Factor Prioritisation (FP) setting. Following this setting, data collection of the variables with the largest S_i should be prioritised for optimising predictions calculated with ForestGALES. Conversely, to identify those variables which negligibly contribute to the variance of the CWS, I adopted the SA setting Factor Fixing (FF), which is based on S^T_i. When the S^T_i of a variable was found to be close to zero, I fixed that variable to different values within its range, and re-ran the simulations with ForestGALES, while maintaining the variation in all the other variables. For discrete variables, I explored all the possible values. For continuous variables, I focussed on the minimum, maximum, and mean values. I then compared the original $CWS_{(B, O)}$ with those calculated after fixing a non-influential variable using scatterplots. I used the method of Sobol' et al. (2007) for the estimation of the approximation error when fixing non-influential variables. The authors have shown that for orthogonal (i.e. non-correlated) factors this is equal to twice the value of the S^T_i of the uninfluential variables, and that it also applies to groups of variables. In the case of multiple non-influential variables, I repeated these procedures for all the combinations of the values of the relevant variables.

5.2.2.3.2 Probabilities of damage

For $Prob_{(B, O)}$ I applied the Factor Mapping (FM) setting of sensitivity analysis, which is based on Regionalised Sensitivity Analysis (e.g. Hornberger and Spear, 1981), a procedure belonging to the family of Monte Carlo Filtering methods. As described in Chapter 2, I have divided the output space in a behavioural region and a non-behavioural region, setting the threshold at $Prob_{(B, O)} = 0.1$ (i.e. a 10% probability of damage). That is, when the calculated $Prob_{(B, O)}$ were smaller than 0.1, I assigned the model run to the corresponding behavioural regions, and to the non-behavioural ones otherwise. I mapped the outputs to the values of the input variables, and investigated the sensitivity of ForestGALES to DAMS, and to the other inputs that were flagged as influential in the calculations of the respective CWS. I have chosen the input variables subject to the FM setting on the basis that DAMS is the only user-input variable directly involved in the wind climate model, and logically a non-influential variable for the calculation of $CWS_{(B,O)}$ cannot drive variation in the

corresponding $Prob_{(B, O)}$. To investigate the sensitivity of the wind climate module to these variables, I plotted their marginal cumulative distribution functions (CDF) conditional on the behavioural and non-behavioural realisations of the model. I estimated the sensitivity of the model to these variables with Smirnov two-sample (two sided) tests, which determine the significance of the differences between the behavioural and non-behavioural CDFs (Saltelli et al., 2008). In order to investigate the second order interactions between these variables, I used two-dimensional density plots to identify the regions in the bivariate input space that are more likely to result in behavioural or non-behavioural realisations of ForestGALES.

5.2.2.4 Differences between species

Tree species is used in ForestGALES as a trigger to activate the corresponding sub-modules where a number of tree characteristics such as canopy dimensions are calculated. Similarly, the values of C_{reg} for different combinations of soil type and rooting depth, the species-specific values of the density of green wood, and the Modulus of Rupture and the Modulus of Elasticity of green wood, are stored in these sub-modules. To explore whether differences between species exist in the ranking of the variables that drive most of the variance in $CWS_{(B,O)}$, I used a ranking method based on Savage scores (Savage, 1956). Coefficients of concordance were used as described by Iman and Conover (1987) and Helton et al. (2005) to compare the importance ranking of input variables between species. For each species, the *m* input variables are ranked in order of their importance (expressed as their S^T_i), reversely in comparison to the procedure used in standard rank regressions; that is, the variable with the highest S^T_i is given a rank $r(S^T_i)$ of 1, the variable with the second highest S^T_i a rank of 2, and so on. This procedure is often used to calculate Kendall's coefficients of concordance (KCC), which assign equal weight to each rank. However, because the purpose of a sensitivity analysis is to identify the most important variables (i.e. those with the top ranks), KCC are inappropriate (Helton et al., 2005). Therefore, the ranks are replaced by the corresponding Savage scores to emphasise the importance of the top ranks, as described in Iman and Conover (1987). For this, I have adopted Eq. (5.2), adapted from Helton et al. (2005).

$$ss(S_i^T) = \sum_{j=r(S_i^T)}^{m} 1/j \qquad \textbf{(5. 2)}$$

where *ss(.)* indicates the Savage scores of variable X_i, and the *m* model input variables are ranked in descending order of importance according to their S^T_i. In the present study *m* = 6, as species is the variable under scrutiny here. Averages are calculated in the event of ties (Iman and Conover, 1987). This substitution allows the calculation of the top-down coefficient of concordance amongst all species (C_T), with Eq. (5.3), adapted from Iman and Conover (1987) and Helton et al. (2005):

$$\boldsymbol{C_T = \left\{\sum_{j=1}^{m}\left[\sum_{q=1}^{nS} ss_q(S_i^T)\right]^2 - nS^2m\right\} \Big/ \left\{nS^2\left(m - \sum_{j=1}^{m} 1/j\right)\right\}} \quad \textbf{(5. 3)}$$

where *nS* is the number of species (here, *nS* = 3). To calculate a value of correlation amongst all the species I used an index developed by Iman and Conover (1987). The authors showed that

$$\boldsymbol{T_{all} = nS(m-1)C_T} \quad \textbf{(5. 4)}$$

follows a chi-square distribution with (*m* – 1) degrees of freedom, with the subscript "*all*" indicating a value of correlation amongst all the species. Hence, a comparison between T_{all} and a chi-square distribution with d.f. = 5 provides a *p*-value to test the null hypothesis of independence of the importance rankings of the input variables between different species. That is, a small *p*-value would prompt me to reject the null hypothesis, and would indicate that the rankings of the most important input variables are similar between species.

In order to delve further into the differences between pairs of species, a similar test was carried out with Pearson correlation coefficients adapted for Savage scores when *nS* = 2, as shown by Iman and Conover (1987). For each pairing of species *α* and *β*, Savage scores were applied to the rankings of their S^T_i with Equation (5.2). The top-down coefficient of concordance between each pair was then calculated with Eq. (5.5), adapted from Iman and Conover (1987) and Helton et al. (2005).

$$\boldsymbol{r_T = \left(\sum_{j=1}^{m} ss_{\alpha_j} ss_{\beta_j} - m\right) \Big/ \left(m - \sum_{j=1}^{m} 1/j\right)} \quad \textbf{(5. 5)}$$

where $ss_{\alpha i}$ and $ss_{\beta i}$, (j = 1,…,*m*) are the Savage scores for the rankings of the *m* S^T_i for species *α* and *β*, respectively. The significance of the differences between each pair of species is then evaluated against a chi-square distribution with (*m* – 1) degrees of freedom, using an adaptation of Eq. (5.4).

$$T_{\alpha,\beta} = 2(m-1)r_T \quad \textbf{(5. 6)}$$

The Results section is divided in three parts: the first one shows the results of the GSA for the $CWS_{(B,O)}$ calculated in the GALES module. The second part shows the similarities in ranking of sensitivity indices between species. The third part describes the GSA results for the $Prob_{(B,O)}$ calculated with the wind climate module. In the first and third parts the three species are presented one at a time.

5.3 Results

Throughout this section, I first show the results for *P. sitchensis*, followed by *P. pinaster*, and lastly *E. globulus*.

5.3.1 Critical Wind Speeds – Sensitivity in the GALES module

5.3.1.1 P. sitchensis

For *P. sitchensis*, the sensitivity of the GALES module to the input variables summarised in Table 5.2 (DAMS aside) is shown in Figure 5.2. The Sobol' sensitivity indices are shown for $CWS_{(B,O)}$.

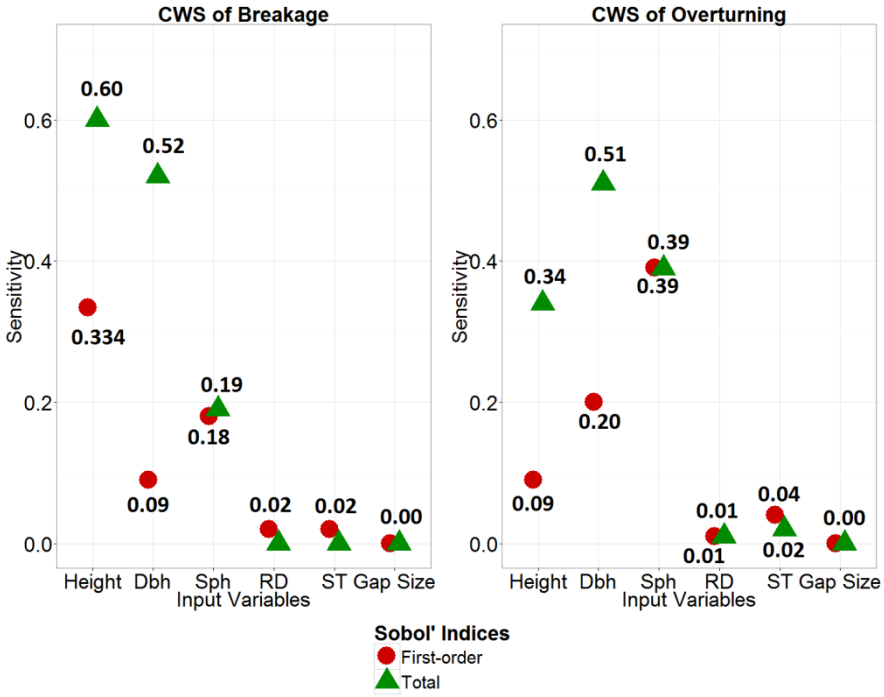


Figure 5.2 - Sobol' first-order and total sensitivity indices for the critical wind speeds for breakage and overturning for *P. sitchensis*. Dbh: diameter at breast height; Sph: stems per hectare. RD: rooting depth. ST: soil type. The total indices of RD, ST, and Gap size for CWS_B are 0.00. The total index of Gap size for $CWS_{(B,O)}$ is 0.00.

As seen in Figure 5.2, Tree height, Dbh, and Sph are the variables to which the $CWS_{(B,O)}$ are most sensitive, although their importance ranking differs between the two CWS, as shown by their S^T_i. The large differences between the S^T_i (green triangles) and S_i (red circles) of Tree height and Dbh indicate that these variables are involved in a large number of interactions with other variables, for both breakage and overturning. Seen that the S^T_i of the other variables are never significantly larger than their S_i, these interactions are mainly between Tree height and Dbh themselves. As expected, Rooting depth and Soil type do not contribute to the variation of CWS_B. These two variables are only marginally influential with regards to CWS_O, with Rooting depth being more important than Soil type. The size of an upwind brown Gap is uninfluential to the calculations of $CWS_{(B,O)}$. Despite the moderate correlation between Rooting depth and Soil type (-0.35, see Table 5.4), I calculated the average approximation errors when the three uninfluential variables are fixed on a nominal value, using the method of Sobol' et al. (2007). This method has only been tested for non-correlated variables; therefore the error estimate might not be entirely accurate. The errors are shown in Table 5.5. For *P. sitchensis*, fixing Rooting depth or Soil type to a value within

their range would result in an average approximation error of 2% and 4%, respectively, of CWS_O. If Rooting depth and Soil type were completely non-correlated, fixing both variables would therefore cause an approximation error of 6%.

Table 5.5 - Average approximation errors in the calculations of the critical wind speeds when fixing Rooting depth, Soil type, and Gap size

	P. sitchensis		*P. pinaster*		*E. globulus*	
	CWS_B	CWS_O	CWS_B	CWS_O	CWS_B	CWS_O
Rooting depth	0%	2%	0%	6%	0%	0%
Soil type	0%	4%	0%	6%	0%	0%
Gap size	0%	0%	0%	0%	6%	8%

Because the S^T_i of Rooting depth, Soil type, and Gap size are practically zero for both CWS, I re-ran the simulations with ForestGALES using the same dataset apart from the values of these variables, which were fixed one at a time to different values within their range. For Rooting depth and Soil type, these are the discrete values in Table 5.3. For Gap size, I chose 0m, 2 times Tree height, 1000m, and 10 times Tree height. The latter was chosen because ForestGALES contains a trap in its code by which an upwind gap cannot be larger than that. I chose to fix Gap size to 2 times Tree height because Gardiner et al. (1997) have shown that it corresponds to the limit of the increase in bending moment coefficient with increasing Gap size. The scatterplots for Rooting depth and Soil type investigated one at a time are shown, for the three species and both CWS, in Appendix C. I anticipate here that the effect of these two variables on CWS_B was confirmed as null by the scatterplots shown in Appendix C. For this reason, in this section I limit myself to showing the scatterplots for Gap size alone, and for combinations of values of Rooting depth and Soil type, for Gap size fixed at 10 times Tree height. For Gap size, I show the scatterplots for both CWS because, despite not being numerically identified as influential by my GSA, it shows some influence on $CWS_{(B,O)}$. For Rooting depth vs Soil type, I show the effect of fixing them for CWS_O alone. Figures 5.3 and 5.4 show the Gap size scatterplots for $CWS_{(B,O)}$ for the three species

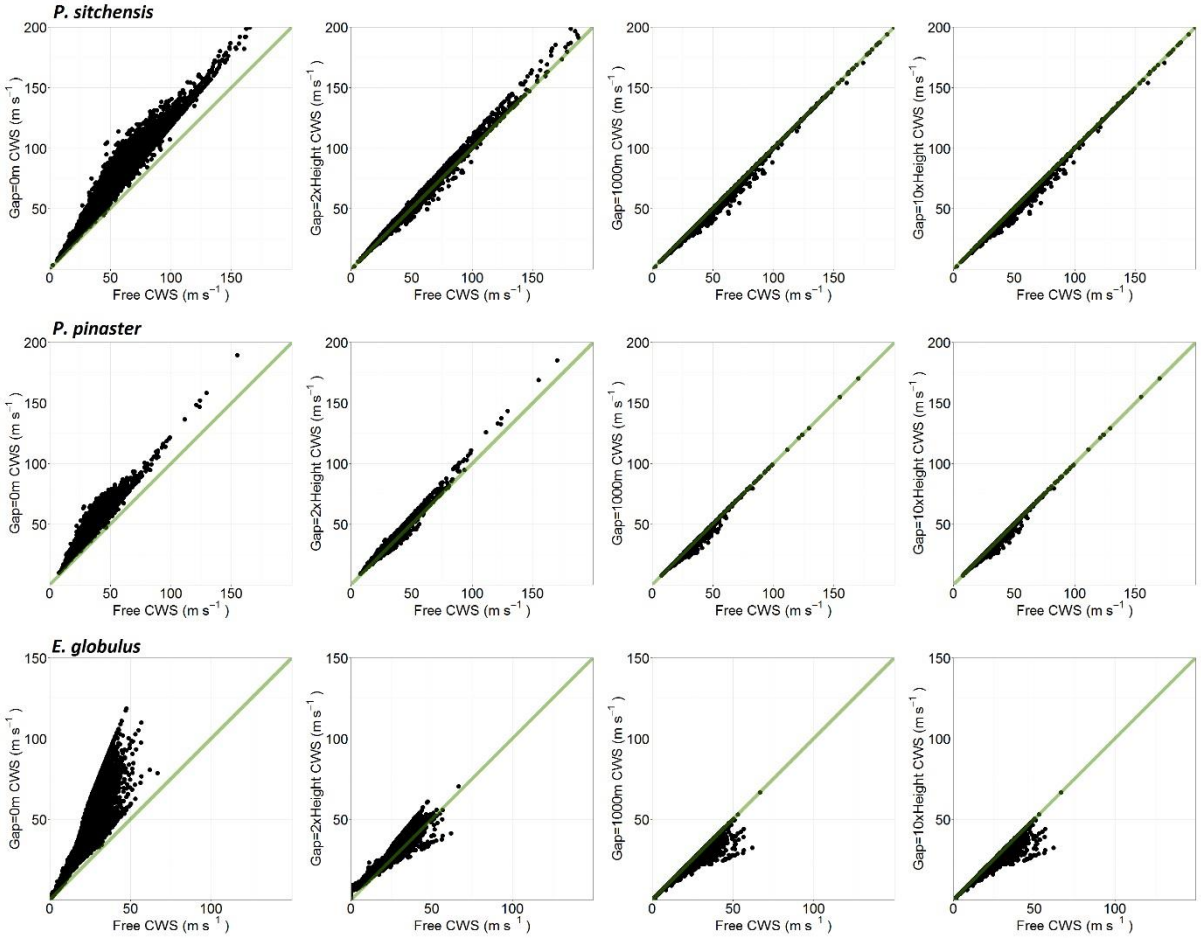


Figure 5.3 - Scatterplots of critical wind speed for breakage for Gap size allowed to vary within its range vs Gap size fixed at four different values. Free: all variables allowed to vary within their ranges; Gap=0m: Gap size fixed at 0m; Gap=2xHeight: Gap size fixed at 2 times Tree height; Gap=1000m: Gap size fixed at 1000m; Gap=10xHeight: Gap size fixed at 10 times Tree height. The green diagonal line represents a 1:1 relationship between the results.

Despite the S^T_i of Gap size being null for *P. sitchensis* and *P. pinaster*, the effect of fixing Gap is evident for all the species, especially when Gap size is fixed at 0m. Fixing Gap size to 0m results in a marked overestimation of CWS_B. Fixing Gap size to 2 times Tree height results in minor overestimation of CWS_B for *P. sitchensis* and *P. pinaster*, while the effect on *E. globulus* is more complex, with equal probabilities of over and underestimation of CWS_B. Fixing Gap size at 1000m or 10 times Tree height has the same result of underestimating CWS_B. The latter is particularly evident for low to medium CWS_B, which correspond to the area of higher wind risk for a forest. The effect of Gap size on CWS_B is more pronounced for *E. globulus*, which is consistent with the approximation error shown in Table 5.5.

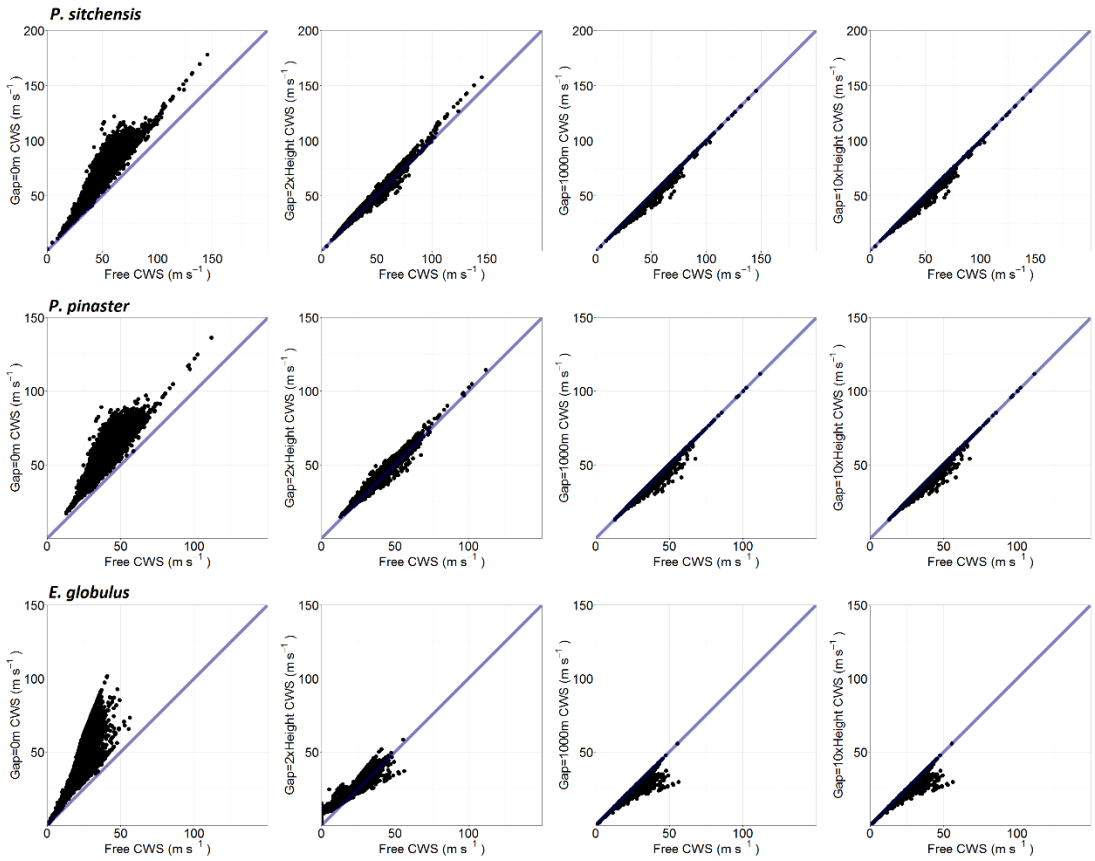


Figure 5.4 - Scatterplots of critical wind speed for overturning for Gap size allowed to vary within its range vs Gap size fixed at four different values. Free: all variables allowed to vary within their ranges; Gap=0m: Gap size fixed at 0m; Gap=2xHeight: Gap size fixed at 2 times Tree height; Gap=1000m: Gap size fixed at 1000m; Gap=10xHeight: Gap size fixed at 10 times Tree height. The blue diagonal line represents a 1:1 relationship between the results.

The scatterplots in Figure 5.4 show the effect of fixing Gap size on CWS_O. The plots mirror those for CWS_B shown in Figure 5.3, with the difference that the range of damaging wind speeds is smaller for overturning than for breakage. For *E. globulus*, fixing Gap size at 2 times Tree height results in a pattern even more complex for CWS_O than for CWS_B, as also very low values are affected. Figure 5.5 shows the *P. sitchensis* CWS_O scatterplots for the different levels of Rooting depth and Soil type, with Gap size fixed at 10 times Tree height.

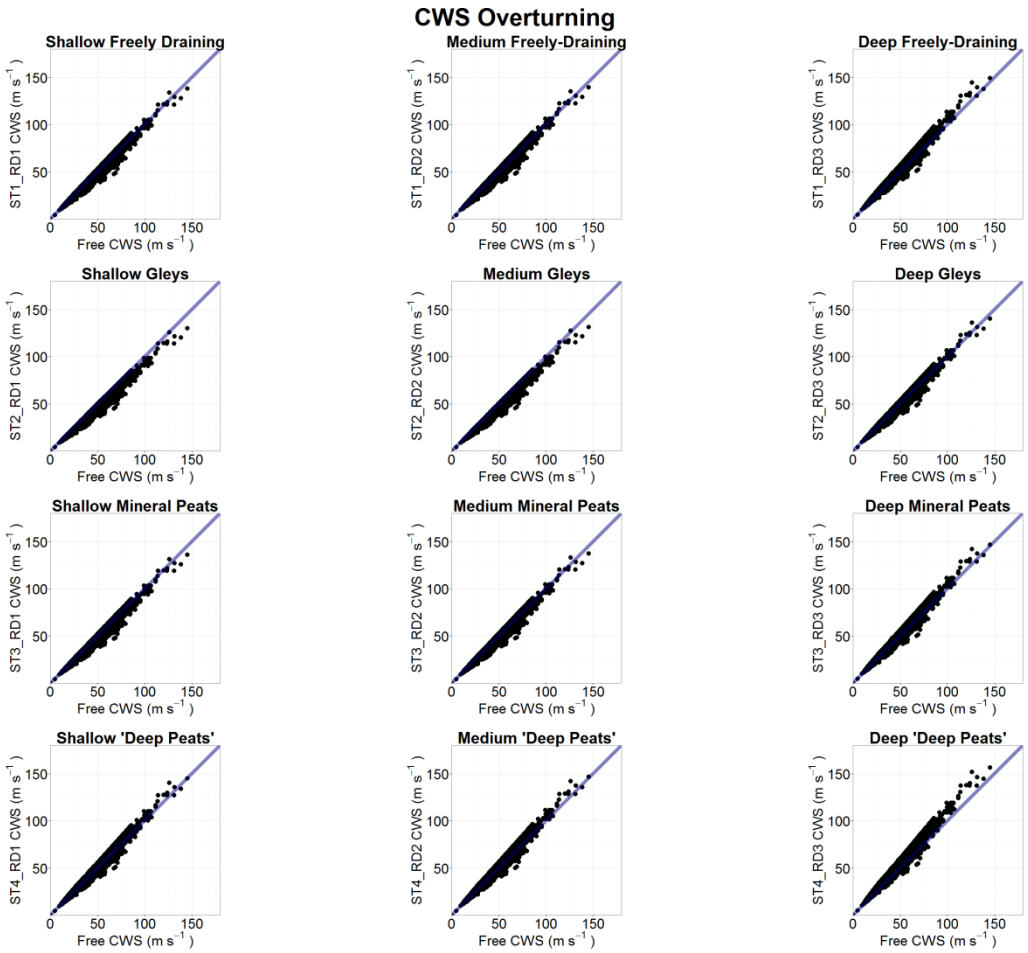


Figure 5.5 - Scatterplots of critical wind speed for overturning for *P. sitchensis*. Simulations with variation in all the inputs vs simulations where Rooting depth and Soil type were fixed at a value within their range. Gap size fixed at 10 times tree height. The green diagonal line represents a 1:1 relationship between the results. "Free" on the abscissa indicates simulations for which all variables were allowed to vary within their range. The coding for the ordinate axis indicates the values at which Soil type (ST) and Rooting depth (RD) were fixed. E.g. "ST1_RD1" indicates Soil type 1 (Freely draining) and Rooting depth 1 (Shallow).

Fixing Rooting depth at "deeply rooted" results in slight overestimations of the CWS_O (i.e. the cloud of points shifts upwards), regardless of Soil type. The same effect is obtained when fixing Soil type at "Freely Draining" and "Deep Peats", regardless of Rooting depth. Fixing Soil type at "Gleys" and "Mineral Peats" results in a slight underestimation of the CWS_O, apart from the already mentioned case of deep Rooting depth. The shape of the clouds of points is partially affected by fixing Gap size (see Figure 5.4).

5.3.1.2 P. pinaster

Figure 5.6 shows the indices of Sobol' for *P. pinaster*.

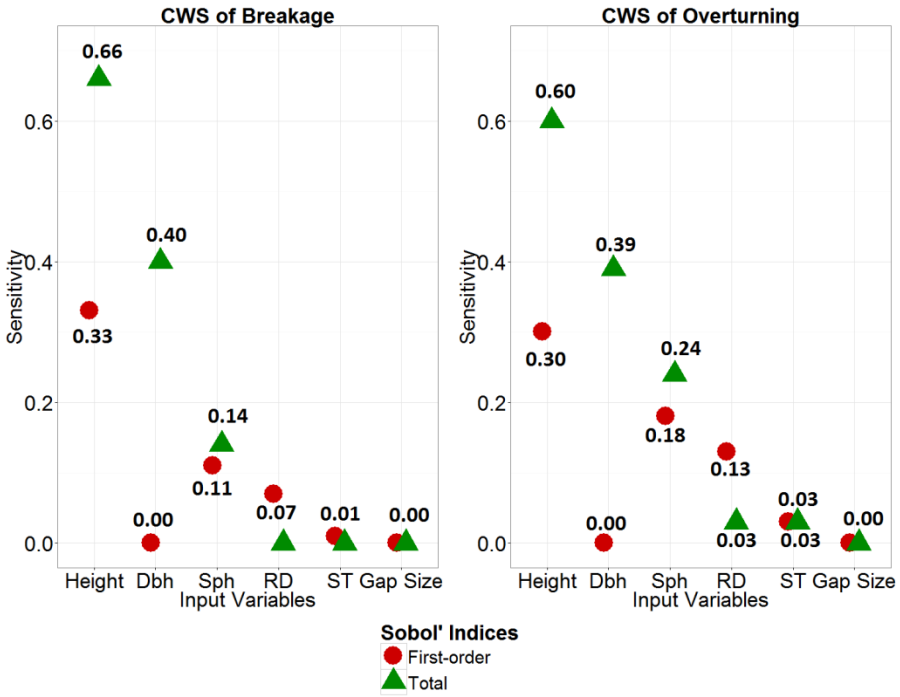


Figure 5.6 - Sobol' first-order and total sensitivity indices for the critical wind speeds for breakage and overturning for *P. pinaster*. Dbh: diameter at breast height; Sph: stems per hectare. RD: rooting depth. ST: soil type. The total indices of RD, ST, and Gap size for CWS_B are 0.00. The total index of Gap size for CWS_O is 0.00.

Figure 5.6 shows that, for *P. pinaster*, the most influential variables are, in decreasing order: Tree height, Dbh, and Sph, for both CWS. The large differences between the S^T_i and S_i seen for *P. sitchensis* are found also for *P. pinaster*, indicating large interactions. Sph is likely to participate more prominently than for *P. sitchensis*, as its S^T_i is slightly larger than its S_i, especially for CWS_O. Rooting depth's S_i for CWS_B is marginal (0.07), suggesting that the moderate correlation with the highly influential Tree height (0.22, see Table 5.4) is responsible for this non-zero value. For CWS_O, Rooting depth is more influential than Soil type. Gap size is not influential for either CWS. Following Sobol' et al. (2007), because of the correlation between Soil Type and Rooting depth, it is not possible to know exactly the average error that fixing Rooting depth and Soil type would result in. However, their correlation is only moderate. As previously shown in Table 5.5, fixing Rooting depth and Soil type would result in a 6% average approximation error for CWS_O, and potentially a 12% cumulative error if both were fixed. As for *P. sitchensis*, I compared the "Free" model simulations with simulations where Rooting depth, Soil type, and Gap size were fixed at

various levels within their ranges. The independent results for Rooting depth and Soil type are shown in Appendix C. Figure 5.7 shows the scatterplots for CWS_O for *P. pinaster*.

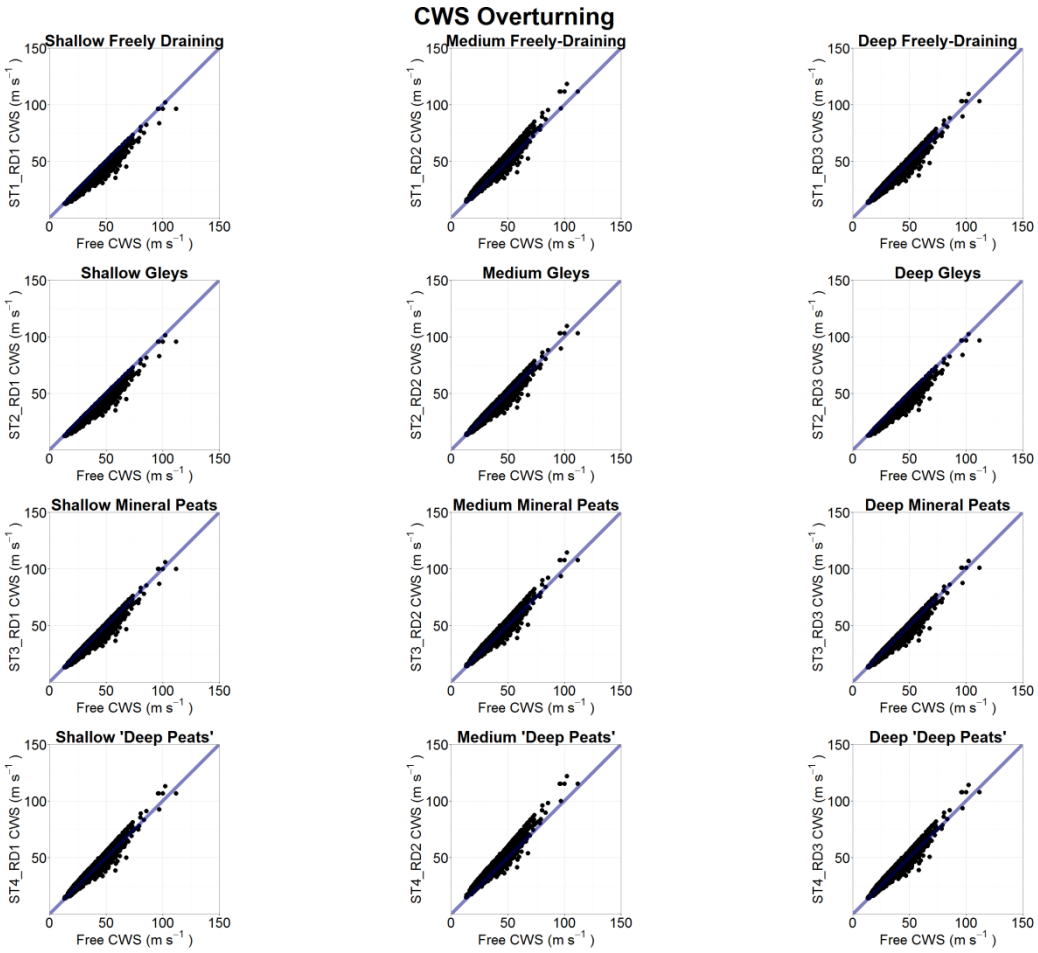


Figure 5.7 - Scatterplots of critical wind speed for overturning for *P. pinaster*. Simulations with variation in all the inputs vs simulations where Rooting depth and Soil type were fixed at a value within their range. Gap size fixed at 10 times tree height. The blue diagonal line represents a 1:1 relationship between the results. "Free" on the abscissa indicates simulations for which all variables were allowed to vary within their range. The coding for the ordinate axis indicates the values at which Soil type (ST) and Rooting depth (RD) were fixed. E.g. "ST1_RD1" indicates Soil type 1 (Freely draining) and Rooting depth 1 (Shallow).

The scatterplots in Figure 5.7 show the effect of fixing Gap size, Rooting depth and Soil type on CWS_O calculated for *P. pinaster*. As for *P. sitchensis*, the effect is mainly visible at medium to high CWS_O. In fact, for both species the S^T_i and the average approximation error of Gap size (Table 5.5) are similar. As shown in Figure 5.4, fixing Gap size to values other than 0m has the same effect as for *P. sitchensis*, causing an underestimation of CWS_O. Fixing Rooting depth at "medium rooted" results in slight overestimations of the CWS_O, regardless of Soil type. Simulations where Soil type was fixed at "Deep Peats" show a slight

overestimation of the CWS_O regardless of Rooting depth, while the simulations where Soil type was fixed at "Gleys" show a slight underestimation of the CWS_O (excluding the case of medium Rooting depth).

5.3.1.3 E. globulus

Figure 5.8 shows the indices of Sobol' for *E. globulus*.

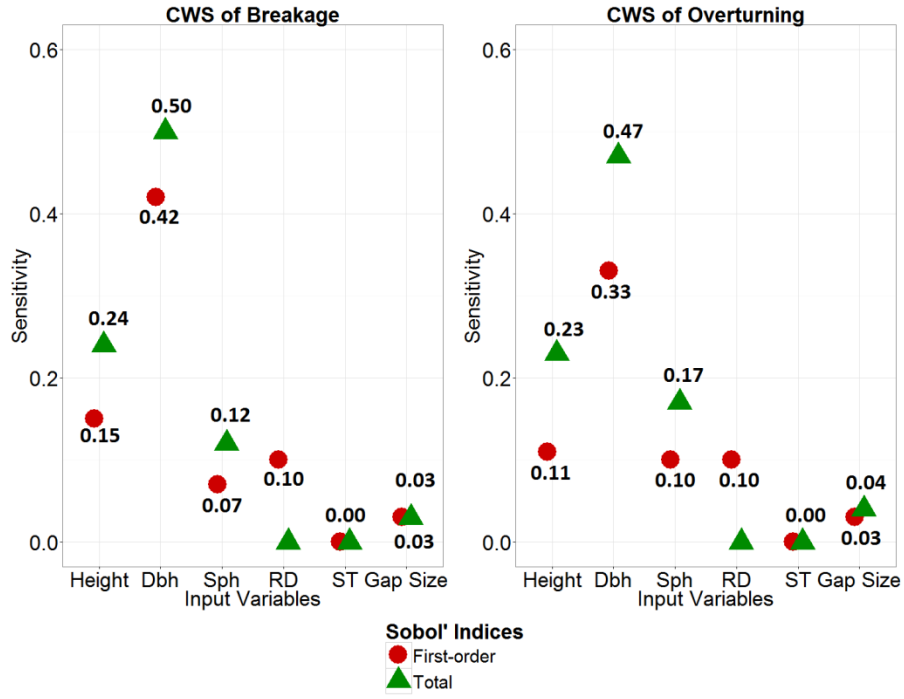


Figure 5.8 - Sobol' first-order and total sensitivity indices for the critical wind speeds for breakage and overturning for *E. globulus*. Dbh: diameter at breast height; Sph: stems per hectare. RD: rooting depth. ST: soil type. The total indices of RD, and ST for CWS_B and for CWS_O are 0.00.

As seen in Figure 5.8, the most influential variables for *E. globulus* are, in decreasing order: Dbh, Tree height, and Sph for both CWS. The differences between the S^T_i and S_i seen for the other two species are less pronounced for *E. globulus*, indicating somewhat smaller interactions. As for *P. pinaster*, Sph is likely to participate in the interactions for *E. globulus*, as its S^T_i is slightly larger than its S_i, especially for CWS_O. The S_i for Rooting depth for both $CWS_{(B,O)}$ are small but significant (0.10). For CWS_B, this is larger than for Sph. For CWS_O, Rooting depth has the same S_i value of Tree height and just smaller than that of Sph for CWS_O. This is partially attributable to the correlations between Rooting depth and the

influential variables Tree height and Dbh, and perhaps to a numerical imprecision in the estimation of Rooting depth's S_i. In fact, the C_{reg} values in the Rooting depth vs Soil type matrix for *E. globulus* are all equal (i.e. Rooting depth and Soil type function as constants for *E. globulus*). This is because, as described in Chapter 3, tree-pulling for this species was only performed on one site with a homogeneous soil, and no significant differences were found between C_{reg} values for different rooting depths. Similarly, I have showed in Chapter 4 that for *E. globulus* the differences in resistance to overturning between shallow and deep rooting are minimal and statistically not significant. This is reflected in the S_i values of Soil type for $CWS_{(B,O)}$ (0 in both cases). Gap size is more influential for both CWS than for the previous two species. In fact, as previously shown in Table 5.5, fixing Rooting depth and Soil type would have no average approximation error for $CWS_{(B,O)}$, while fixing Gap would result in a 6% and 8% errors for CWS_B and CWS_O, respectively. The lack of correlation between Gap size and the other input variables ensures the reliability of this estimate.

Figure 5.9 shows the scatterplots for CWS_O for *E. globulus*, comparing "Free" simulations with "Fixed" simulations. Gap sized was fixed at 10 times Tree height, as for the previous species.

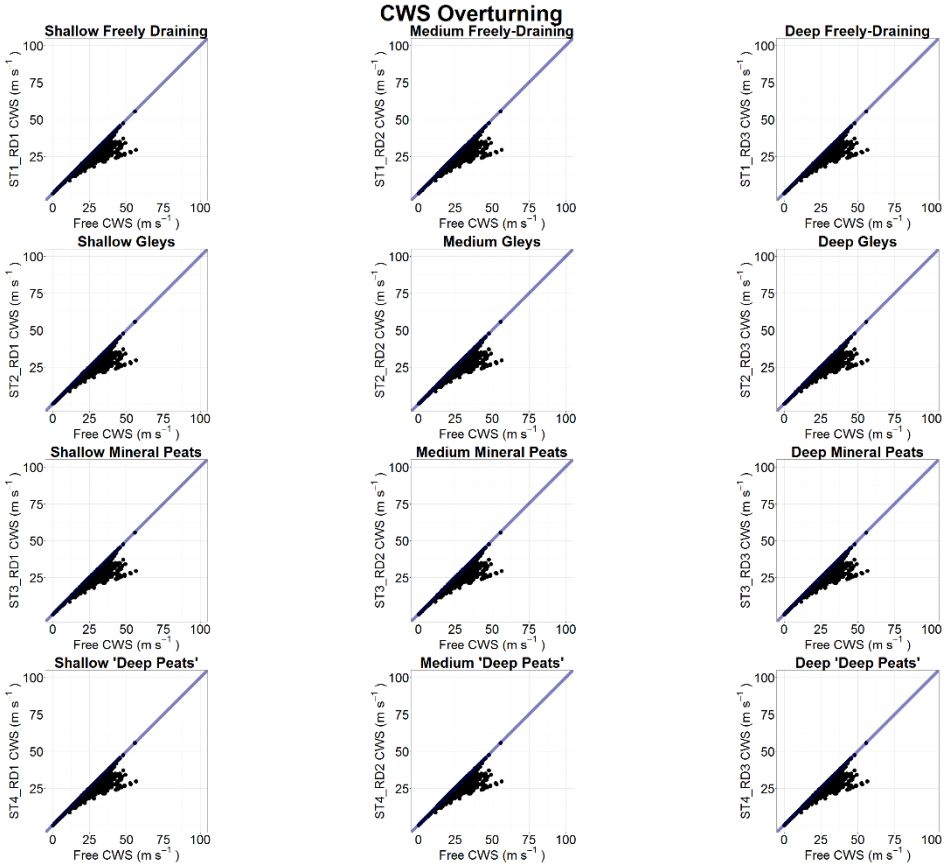


Figure 5.9 - Scatterplots of critical wind speed for overturning for *E. globulus*. Simulations with variation in all the inputs vs simulations where Rooting depth and Soil type were fixed at a value within their range. Gap size fixed at 10 times tree height. The blue diagonal line represents a 1:1 relationship between the results. "Free" on the abscissa indicates simulations for which all variables were allowed to vary within their range. The coding for the ordinate axis indicates the values at which Soil type (ST) and Rooting depth (RD) were fixed. E.g. "ST1_RD1" indicates Soil type 1 (Freely draining) and Rooting depth 1 (Shallow).

The scatterplots in Figure 5.9 confirm that fixing Rooting depth and Soil type has no effect on CWS_O calculated for *E. globulus*. In fact, these plots are identical to those for overturning for different values of Gap size, as shown in Figure 5.4, as they are entirely driven by the error in fixing Gap size.

5.3.2 Differences between species

Table 5.6 shows the *p*-values of the comparisons between the coefficients of concordance for all the species (T_{all}), and for pairs of species ($T_{\alpha,\delta}$), and a chi-square distribution with d.f. = 5. Small *p*-values indicate that the null hypothesis of independence of the importance rankings of the input variables between different species can be rejected. Conversely, large

p-values indicate that the rankings are significantly different between species. Rankings are based on S^T_i values.

Table 5.6 - Significance of correlation between rankings of S^T_i of different species. The H_0 is of independence of rankings between species. Low *p*-values suggest the H_0 should be rejected.

	CWS_B	CWS_O
All species	0.029	0.044
P. sitchensis / *P. pinaster*	0.087	0.448
P. sitchensis / *E. globulus*	0.247	0.128
P. pinaster / *E. globulus*	0.247	0.273

The *p*-values for the comparison between all the species suggest that the rankings of the influential variables for $CWS_{(B,O)}$ are similar for *P. sitchensis*, *P. pinaster*, and *E. globulus*. This is likely due to the fact that the number of species and the number of variables are small. This, together with the fact that, for each CWS, two of the species show some similarities (CWS_B: *P. sitchensis* and *P. pinaster*, *p*-value = 0.087; CWS_O: *P. sitchensis* and *E. globulus*, *p*-value = 0.128), is the likely reason for the significant *p*-values for the comparisons including all the species. In fact, the Savage Scores emphasise the top ranks, and Tree height, Dbh, and Sph rank at the top three for all the species, although sometimes in different order. However, by investigating the pairs of species in more detail, and by referring to Figures 5.3, 5.7, and 5.9, significant differences become evident. For CWS_B, the ranking of the S^T_i of *E. globulus* is markedly different from the other two. In fact, the *p*-values for the comparisons that include *E. globulus* are the largest (0.247), while the *p*-value of the comparison between *P. sitchensis* and *P. pinaster* (0.087) indicates that differences between these two species are almost non-significant. In fact, the S^T_i rankings of these two species are identical (Figures 5.3 and 5.7), which suggests that the accuracy of my statistical test is not perfect.

For CWS_B, the large *p*-values (0.237 and 0.246) for the comparisons between *P. sitchensis* / *E. globulus*, and *P. pinaster* / *E. globulus*, are driven by the fact that the ranking of the top two variables, Tree height and Dbh, are inverted between the pair (*P. sitchensis*, *P. pinaster*), and *E. globulus*. The small, but non-zero S^T_i of Gap for *E. globulus* contributes to these differences. For CWS_O, the difference between *P. sitchensis* and *P. pinaster* (*p*-value 0.448) is due to the different ranks of the top three variables (Tree height, Dbh, and Sph). For the *P. pinaster* / *E. globulus* pair, the large *p*-value (0.273) is due to the rankings of Tree

height, Dbh, and Gap size. Similarly, the difference between *P. sitchensis* and *E. globulus* (*p*-value 0.128) is attributable to the rankings of Tree height, Sph, and Gap size.

5.3.3 Probabilities of damage – Sensitivity in the wind climate module

As stated in the section 5.2, I have set the threshold for the probabilities of damage at 10% (i.e. a probability of 0.1), to differentiate between behavioural ($Prob_{(B,O)} < 0.1$) and non-behavioural ($Prob_{(B,O)} > 0.1$) regions. The CDF plots and the 2D density plots throughout this section are based on this categorisation. In the CDF plots, the values of the D-statistic represent the maximum distance between the CDF curves.

5.3.3.1 P. sitchensis

Figure 5.10 shows the CDF plots for *P. sitchensis* for $Prob_B$, for all the ForestGALES input variables.

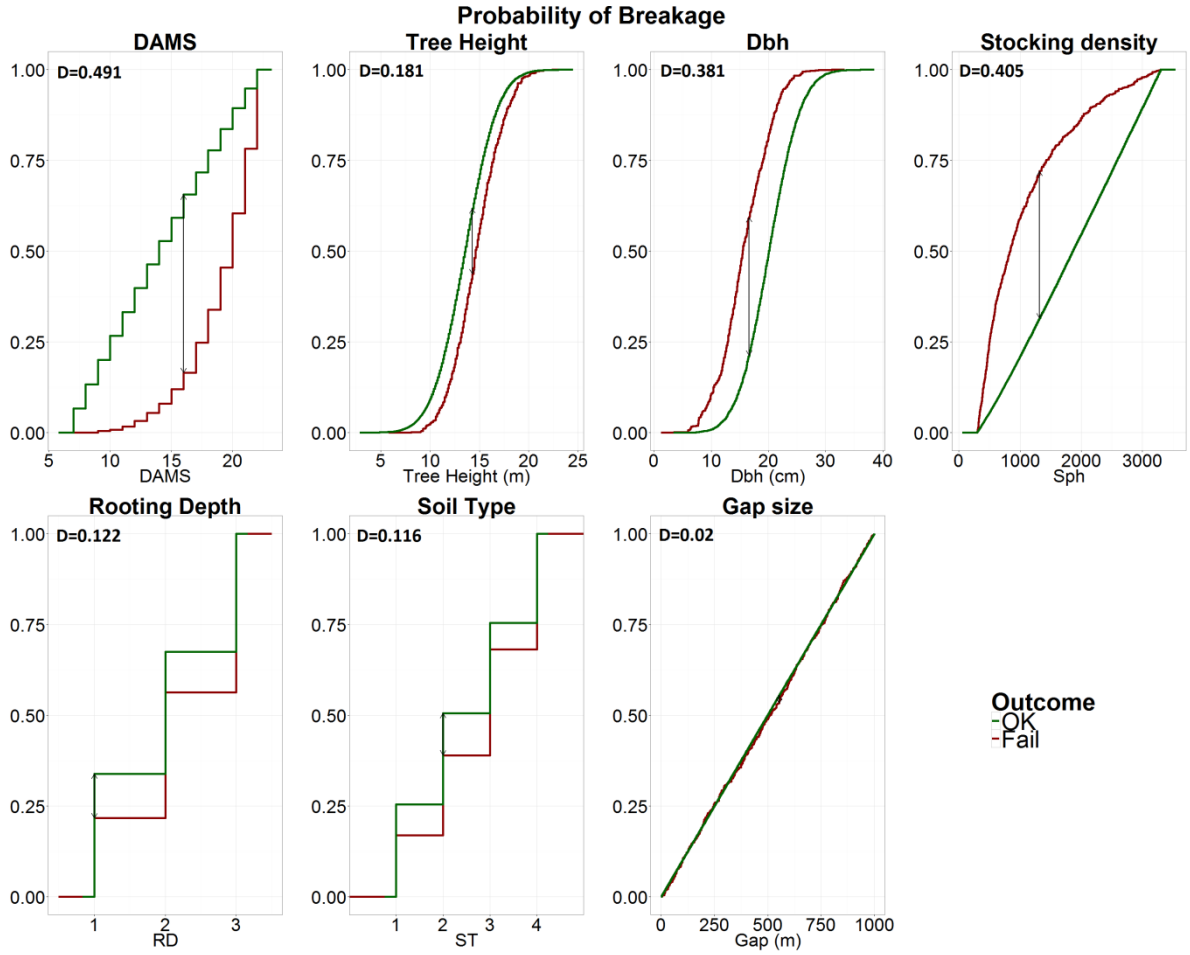


Figure 5.10 - Cumulative density function plots of the probability of breakage for *P. sitchensis*. DAMS: Detailed Aspect Methods of Scoring, a measure of the windiness of the site. Dbh: diameter at breast height; Sph: stems per hectare. The green lines represent model realisation in the behavioural region (probability < 0.1). The red lines represent model realisations in the non-behavioural region (probability > 0.1). The arrows indicate the maximum distance between the cumulative distributions. Large distances indicate that the variable is influential, as described by the values of the D-statistic.

Figure 5.10 shows that, for *P. sitchensis*, the main drivers of the realisations of ForestGALES in the behavioural and non-behavioural regions of $Prob_B$ are Dbh, DAMS, and Sph, followed by Tree Height, while the other variables contributing only marginally. Rooting depth and Soil type show some importance, which is attributable to their correlation with Dbh and Sph, respectively (see Table 5.4). The results for $Prob_O$ are shown in Figure 5.11.

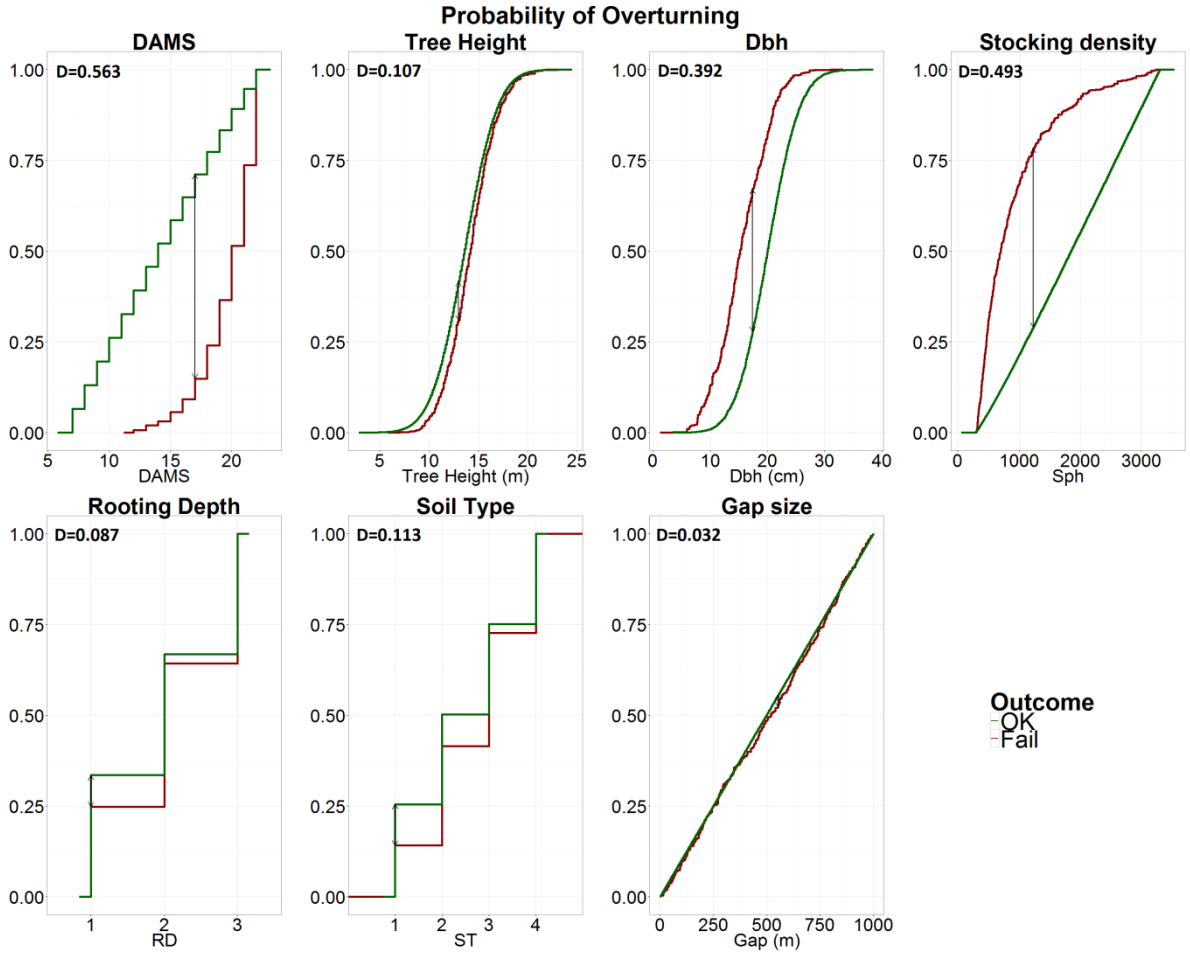


Figure 5.11 - Cumulative density function plots of the probability of overturning for *P. sitchensis*. DAMS: Detailed Aspect Methods of Scoring, a measure of the windiness of the site. Dbh: diameter at breast height; Sph: stems per hectare. The green lines represent model realisation in the behavioural region (probability < 0.1). The red lines represent model realisations in the non-behavioural region (probability > 0.1). The arrows indicate the maximum distance between the cumulative distributions. Large distances indicate that the variable is influential, as described by the values of the D-statistic.

For *P. sitchensis*, the variables driving the variation in $Prob_O$ are similar to those of $Prob_B$, with the only difference being that Tree Height is less important than Soil Type. The influence of Rooting depth is smaller than for $Prob_B$, and that of Soil type is very similar for the two probabilities of damage. These results mirror the relative differences between the respective S^T_i for CWS_B and CWS_O, shown in Figure 5.2.

In order to investigate the two-way interactions between influential variables for $Prob_{(B,O)}$, I used 2D-density plots. I also include Tree height, despite it being flagged as marginally influential for $Prob_{(B,O)}$, because of its high values of S^T_i and S_i. Figures 5.12 and 5.13 show these two-way interactions for *P. sitchensis* for $Prob_B$ and $Prob_O$, respectively. The first

three plots (*a* to *c*) show the interactions between DAMS and one of Tree height, Dbh, and Sph. The last three plots (*d* to *f*) show the interactions between these three variables.

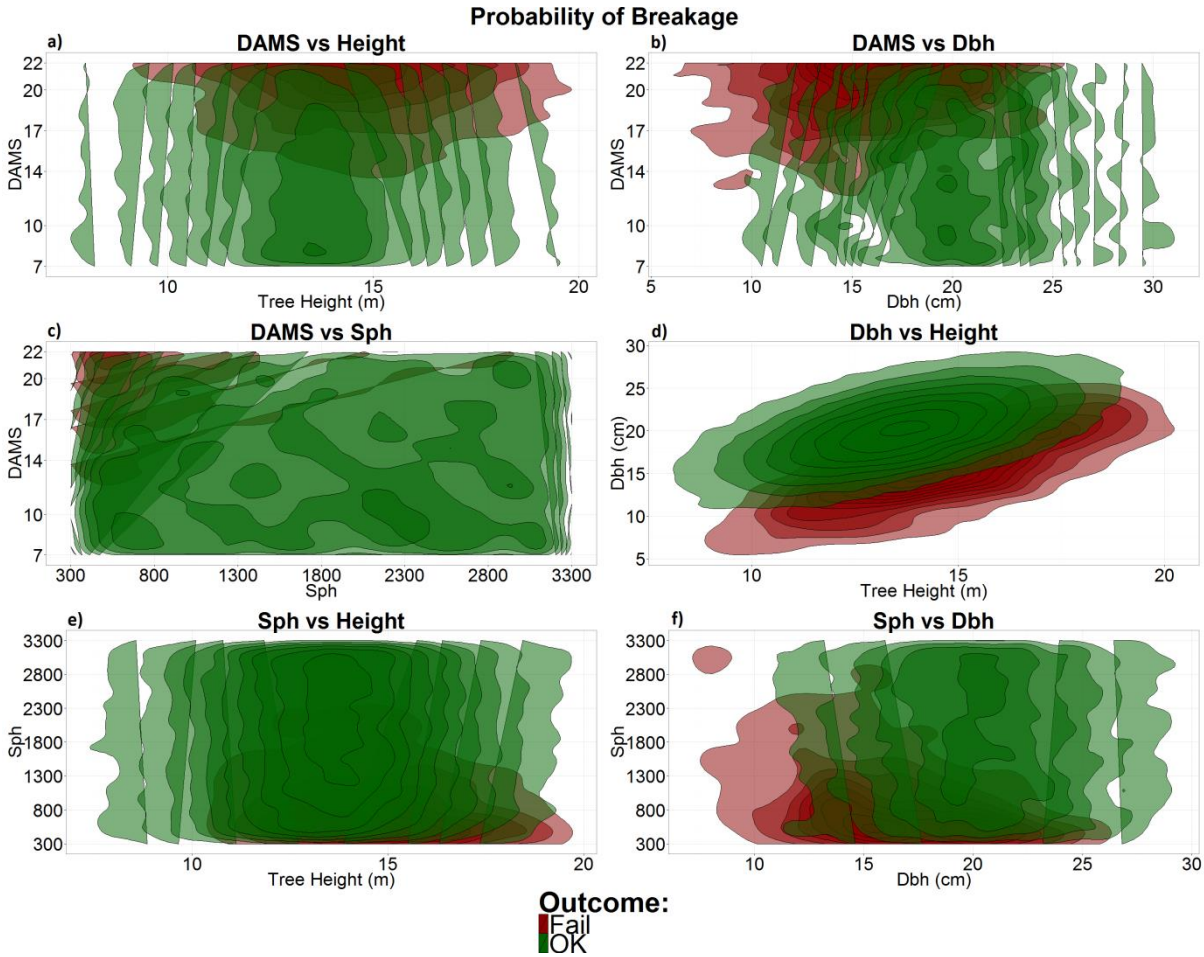
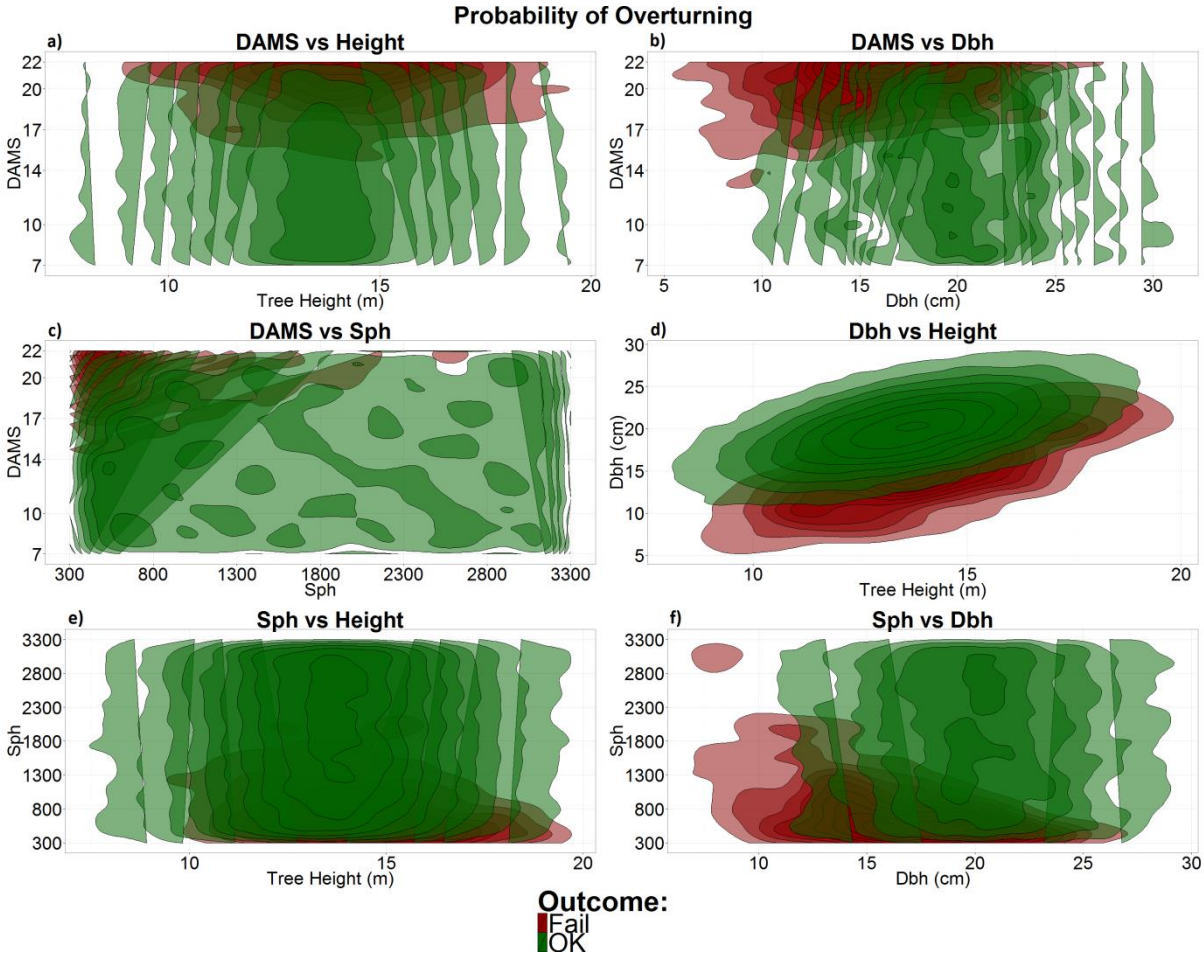


Figure 5.12 - 2D – density plots for probability of breakage for *P. sitchensis*. DAMS: Detailed Aspect Method of Scoring, a measure of the windiness of a site; Dbh: diameter at breast height; Sph: stems per hectare. The green areas represent the realisations of ForestGALES that correspond to a probability of damage < 0.1. The



red areas correspond to probabilities > 0.1. The intensity of the colour corresponds to the density of the outputs: darker areas have higher densities.

Figure 5.13 - 2D – density plots for probability of overturning for *P. sitchensis*. DAMS: Detailed Aspect Method of Scoring, a measure of the windiness of a site; Dbh: diameter at breast height; Sph: stems per hectare. The green areas represent the realisations of ForestGALES that correspond to a probability of damage < 0.1. The red areas correspond to probabilities > 0.1. The intensity of the colour corresponds to the density of the outputs: darker areas have higher densities.

The trends in Figures 5.12 and 5.13 are very similar. Most of the plots show large areas where either damage or no damage can result for the same combinations of the variables in the plots, suggesting that bivariate interactions are not sufficient to discriminate between behavioural ($Prob_{(B,O)} < 0.1$) and non-behavioural ($Prob_{(B,O)} > 0.1$) realisations of ForestGALES. Both Figures show that for *P. sitchensis* ForestGALES predicts damage for medium-sized trees for exposed sites (DAMS over 12, graphs *a* and *b* in Figures 5.12 and 5.13), while shorter trees and trees with a large Dbh are at less risk of damage. The model predicts that trees with Dbh above ~25cm will be safe from damage, regardless of the

severity of the wind, while trees of small diameters will be prone to damage even at low DAMS (Figures 5.12*b* and 5.13*b*). The DAMS vs Sph plots show that ForestGALES predicts that the stands most at risk are those of low stocking densities, although areas of higher probabilities of damage are present for other stocking densities (Figure 5.13*c*). The Dbh vs Height plots show that the model predicts higher probabilities of damage to trees with small Dbh, especially for short trees. The Sph vs Height plots indicate that, regardless of the height of the trees, ForestGALES predicts more damage to stands with low stocking densities, and higher probabilities of damage for trees taller than 10m. As for the interaction between Sph and Dbh, ForestGALES predicts more damage to trees of small diameter, especially for stands of low to medium stocking densities (Figures 5.12*f* and 5.13*f*).

5.3.3.2 P. pinaster

Figure 5.14 shows the CDF plots for *P. pinaster* for the probability of breakage.

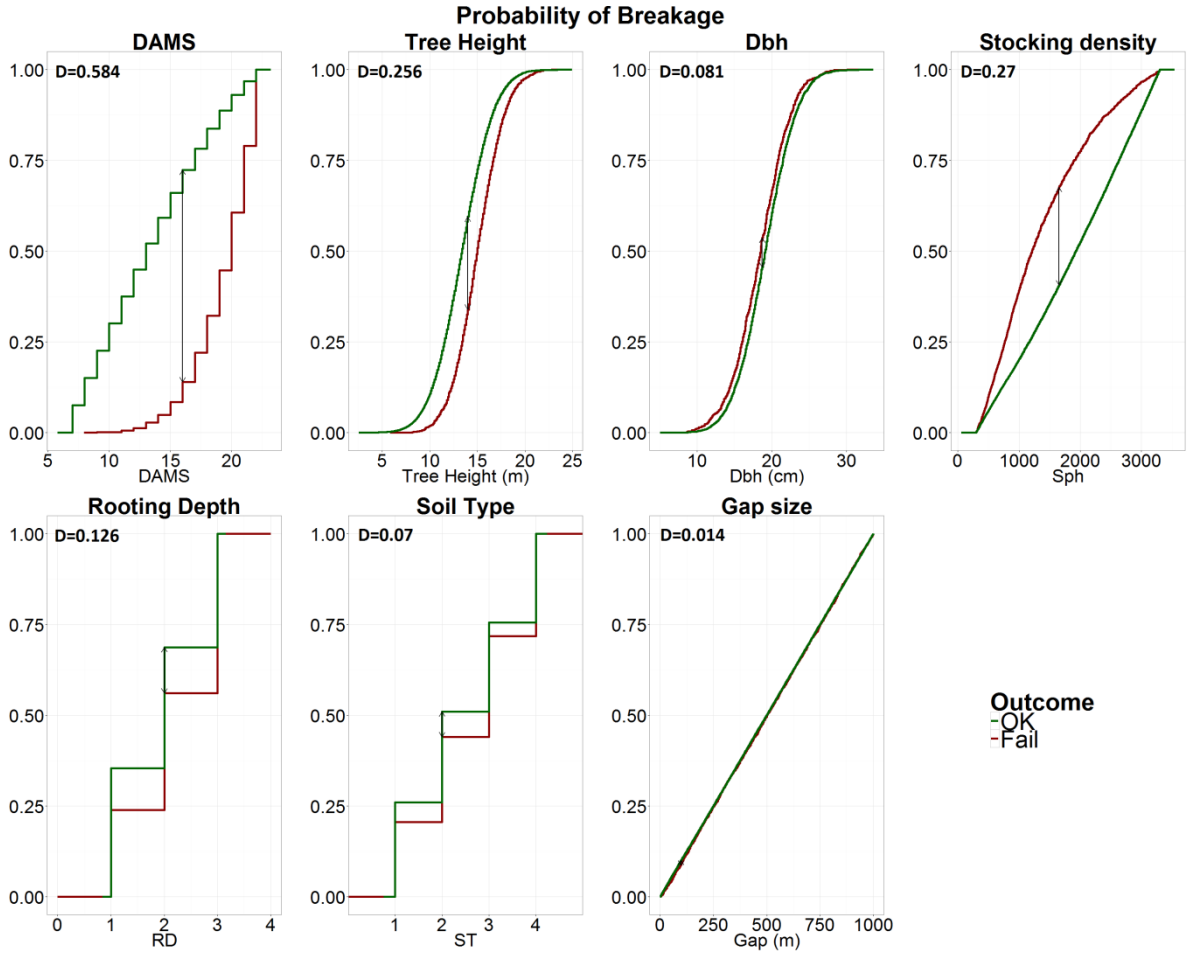


Figure 5.14 - Cumulative density function plots of the probability of breakage for *P. pinaster*. DAMS: Detailed Aspect Methods of Scoring, a measure of the windiness of the site. Dbh: diameter at breast height; Sph: stems per hectare. The green lines represent model realisation in the behavioural region (probability < 0.1). The red lines represent model realisations in the non-behavioural region (probability > 0.1). The arrows indicate the maximum distance between the cumulative distributions. Large distances indicate that the variable is influential, as described by the values of the D-statistic.

Figure 5.14 shows that, for *P. pinaster*, the most influential variables with regards to $Prob_B$ are DAMS, Sph, and Tree height, while the other variables contribute little to the variation in the output. As for *P. sitchensis*, Rooting depth and Soil type show minimal importance, likely attributable to their correlation with Tree height and Sph, respectively, as shown in Table 5.4. Figure 5.15 shows the CDF plots for $Prob_O$.

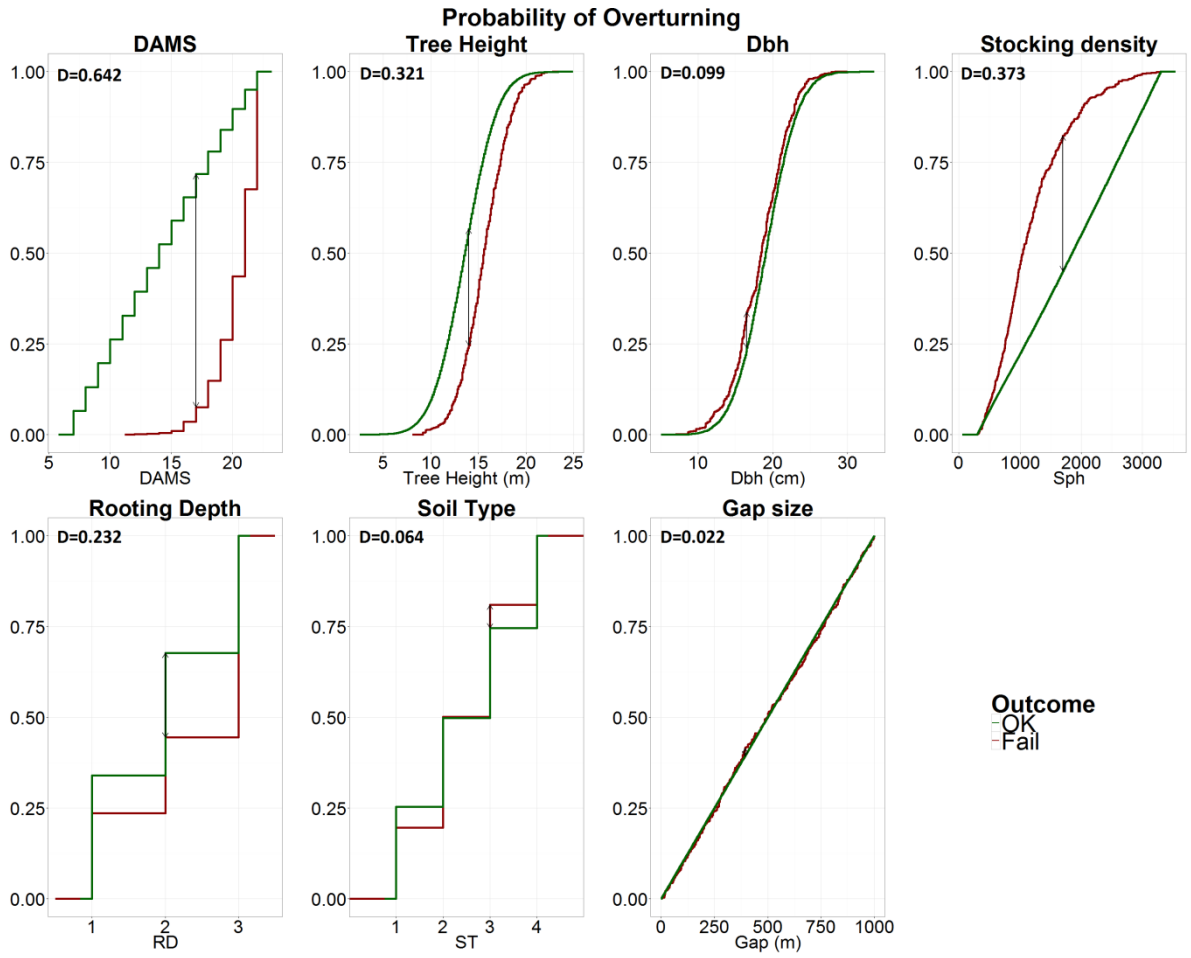


Figure 5.15 - Cumulative density function plots of the probability of overturning for *P. pinaster*. DAMS: Detailed Aspect Methods of Scoring, a measure of the windiness of the site. Dbh: diameter at breast height; Sph: stems per hectare. The green lines represent model realisation in the behavioural region (probability < 0.1). The red lines represent model realisations in the non-behavioural region (probability > 0.1). The arrows indicate the maximum distance between the cumulative distributions. Large distances indicate that the variable is influential, as described by the values of the D-statistic.

The main drivers of variation of $Prob_O$ for *P. pinaster* are the same as those of $Prob_B$ (in decreasing order: DAMS, Sph, Tree height). The value of the D-statistic of Rooting depth is higher for $Prob_O$ (0.232) than for $Prob_B$ (0.126), which reflects the variable's higher S_i for CWS_O than for CWS_B, as seen in Figure 5.6. In Figures 5.16 and 5.17 I show the two-way interactions for *P. pinaster* for the probabilities of breakage and overturning, respectively.

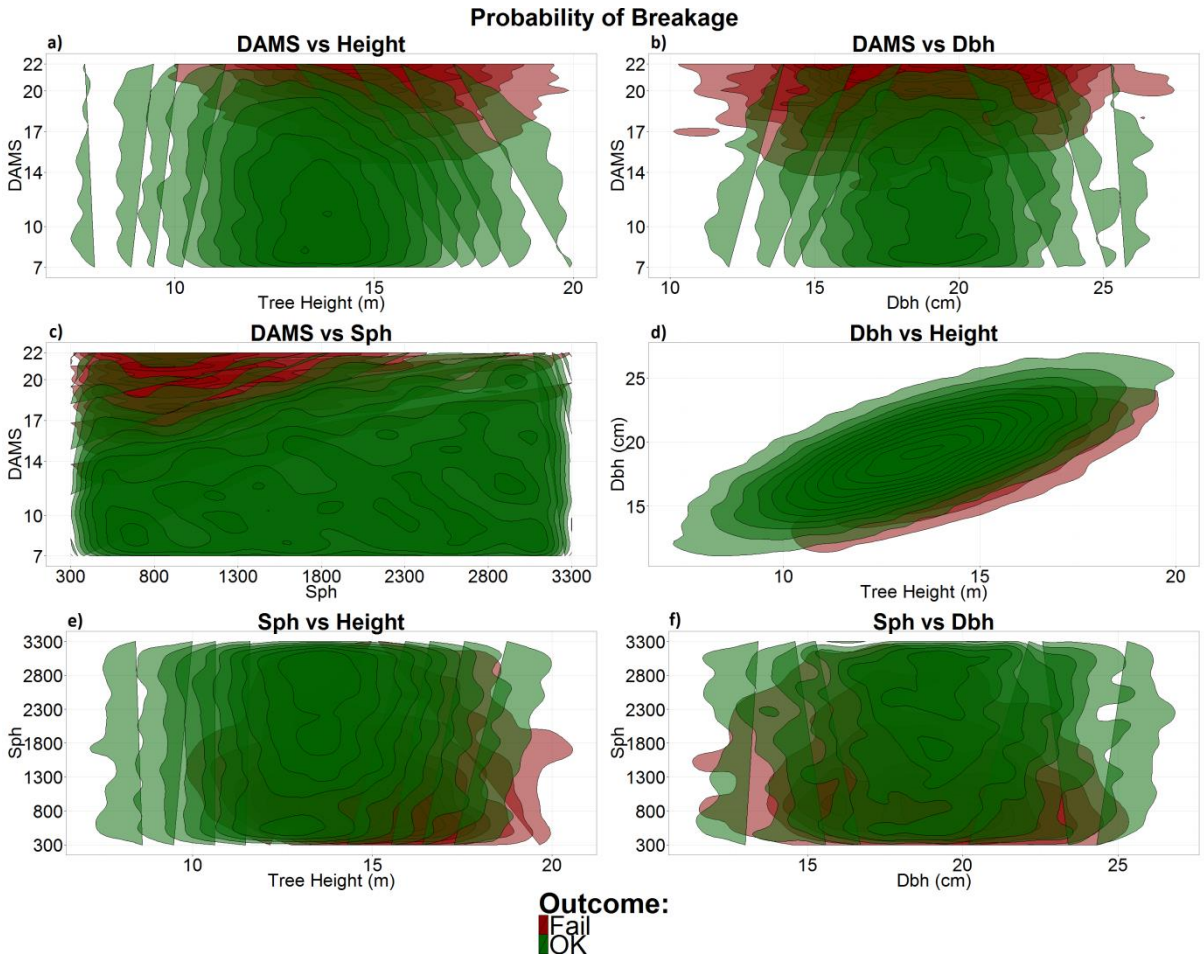


Figure 5.16 - 2D – density plots for probability of breakage for *P. pinaster*. DAMS: Detailed Aspect Method of Scoring, a measure of the windiness of a site; Dbh: diameter at breast height; Sph: stems per hectare. The green areas represent the realisations of ForestGALES that correspond to a probability of damage < 0.1. The red areas correspond to probabilities > 0.1. The intensity of the colour corresponds to the density of the outputs: darker areas have higher densities.

With regards to the interaction between DAMS and Tree height, ForestGALES predicts that short (<10m) *P. pinaster* trees are safe from breakage, and that DAMS lower than 14 are generally safe (Figure 5.16*a*). In fact, below this DAMS values, non-behavioural realisations of ForestGALES ($Prob_{(B,O)}$ > 0.1, shown in red), are absent. This threshold is slightly lower (DAMS =13) for Dbh, whereby larger trees (Dbh > 24cm) are at low risk of breakage for DAMS up to 20 (Figure 5.16*b*). As for *P. sitchensis*, low stocking densities are associated with higher probabilities of damage, although ForestGALES predicts damage to *P. pinaster* stands of high densities (up to 3,300 sph) for DAMS as low as 17 (Figure 5.16*c*). With regards to the interaction between Dbh and Tree height, ForestGALES predicts that tall trees (height > 11m) are as likely to survive as they are to break, regardless of their Dbh,

while short trees with small to medium Dbh, and tall trees with large Dbh are less likely to break (Figure 5.16*d*). The Sph vs Tree height plot shows that short *P. pinaster* trees are at lower risk of breakage regardless of the stocking density of the stand, while tall trees are exposed to a higher risk for low Sph (Figure 5.16*e*). With regards to the interaction between Sph and Dbh, areas of high probability of breakage are widespread in the plot (Figure 5.16*f*). However, ForestGALES predicts that large trees at high stocking densities have a lower probability of damage.

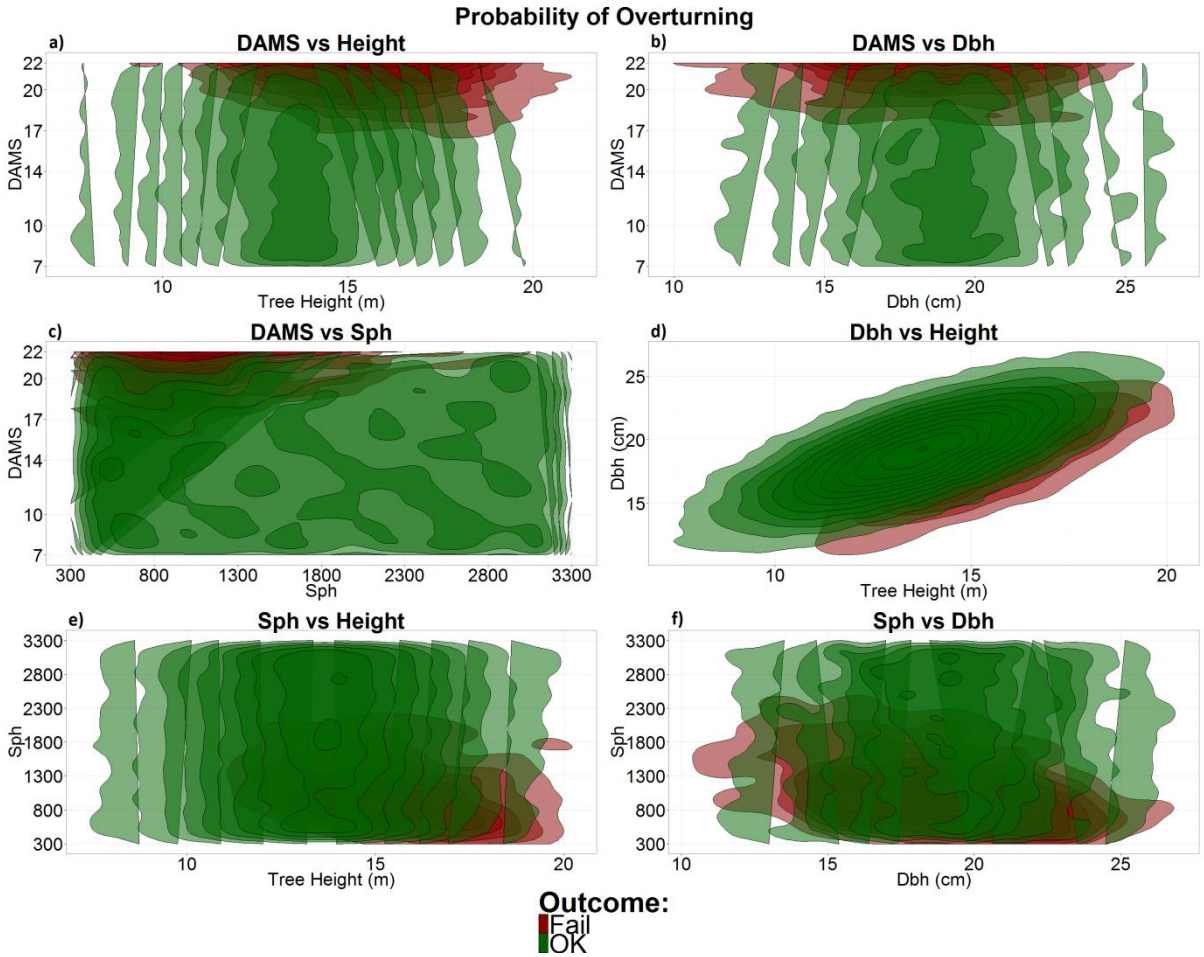


Figure 5.17 - 2D – density plots for probability of overturning for *P. pinaster*. DAMS: Detailed Aspect Method of Scoring, a measure of the windiness of a site; Dbh: diameter at breast height; Sph: stems per hectare. The green areas represent the realisations of ForestGALES that correspond to a probability of damage < 0.1. The red areas correspond to probabilities > 0.1. The intensity of the colour corresponds to the density of the outputs: darker areas have higher densities.

The DAMS plots in Figure 5.17 are considerably clearer than those for $Prob_B$ shown in Figure 5.16, as the areas that describe high and low probabilities of damage are more distinct than those in Figure 5.16. The plots that show the interactions between Tree height, Dbh, and Sph, are similar to those for $Prob_B$. With regards to overturning, ForestGALES predicts that *P. pinaster* trees above a height of ~10m are likely to fail for DAMS > 17 (Figure 5.17*a*). Similarly, ForestGALES predicts that *P. pinaster* trees will overturn when exposed to a wind climate corresponding to DAMS > 17, regardless of their Dbh (Figure 5.17*b*). The DAMS vs Sph plot shows that low stocking densities are at higher risk of overturning for DAMS as low as 11, while DAMS of 20 and above are required to overturn trees in very dense stands. The Dbh vs Tree height plot (figure 5.17*d*) is almost identical to that in Figure 5.16*d*, with trees of height larger than 11m being as likely to survive as to uproot, while short trees are less likely to uproot, regardless of their Dbh. The interactions between Sph and Tree height, and Sph and Dbh, show that higher stocking densities are associated with lower probabilities of overturning, regardless of the height or diameter of the trees. However, short trees (height < 11m) show higher probabilities of survival also at low stocking densities.

5.3.3.3 E. globulus

The CDF plots for *E. globulus* for the probability of breakage are shown in Figure 5.18.

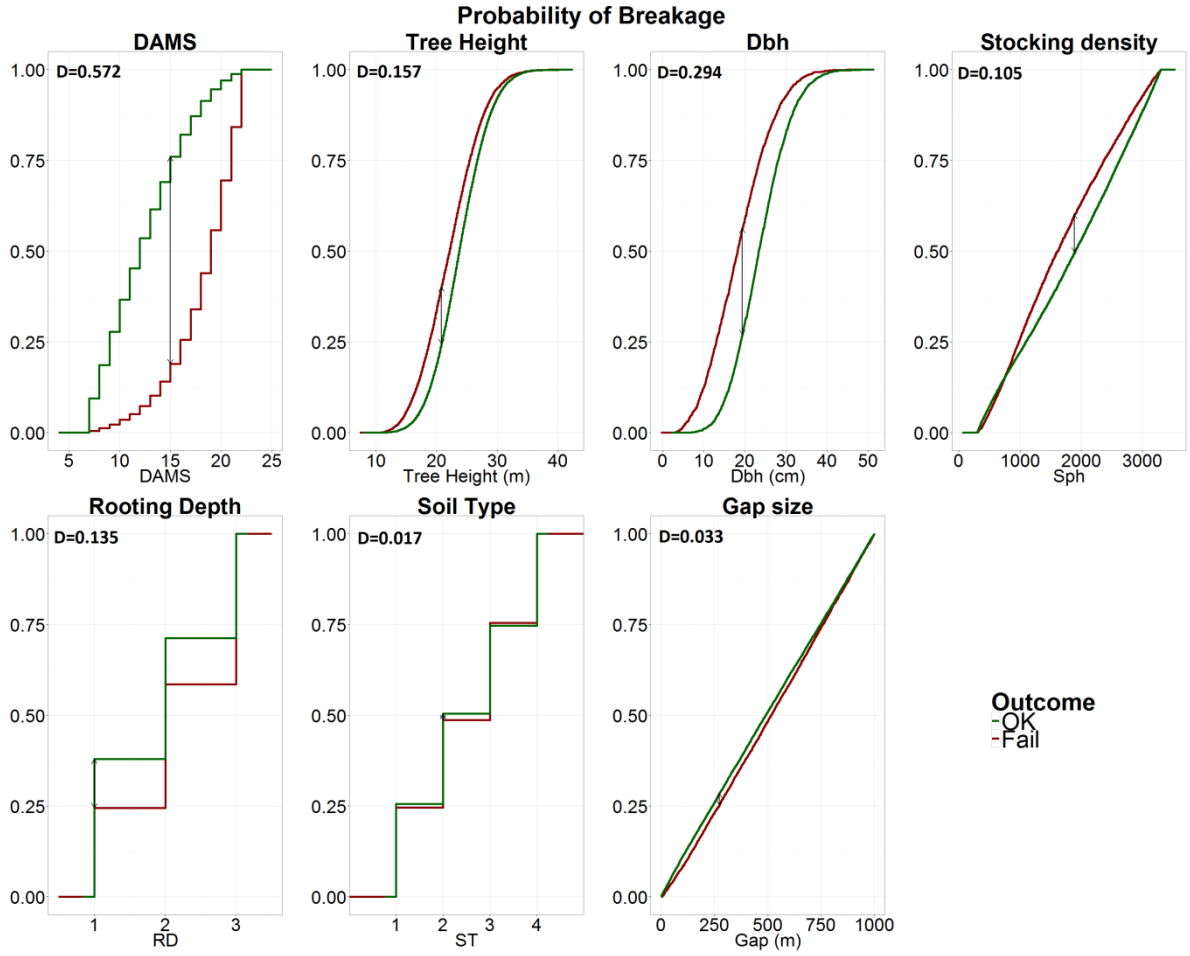


Figure 5.18 - Cumulative density function plots of the probability of breakage for *E. globulus*. DAMS: Detailed Aspect Methods of Scoring, a measure of the windiness of the site. Dbh: diameter at breast height; Sph: stems per hectare. The green lines represent model realisation in the behavioural region (probability < 0.1). The red lines represent model realisations in the non-behavioural region (probability > 0.1). The arrows indicate the maximum distance between the cumulative distributions. Large distances indicate that the variable is influential, as described by the values of the D-statistic.

For *E. globulus*, DAMS is the most important variable for the behavioural and non-behavioural realisations of ForestGALES for $Prob_B$, followed by Dbh and Tree height. As shown in Figure 5.19, for $Prob_O$ DAMS and Dbh, and marginally Sph, are the most important variables to differentiate between the behavioural and non-behavioural regions of the output space. The correlations shown in Table 5.4 between Rooting depth and these two variables are responsible for the relatively high value of the D-statistic for Rooting depth for both $Prob_{(B,O)}$.

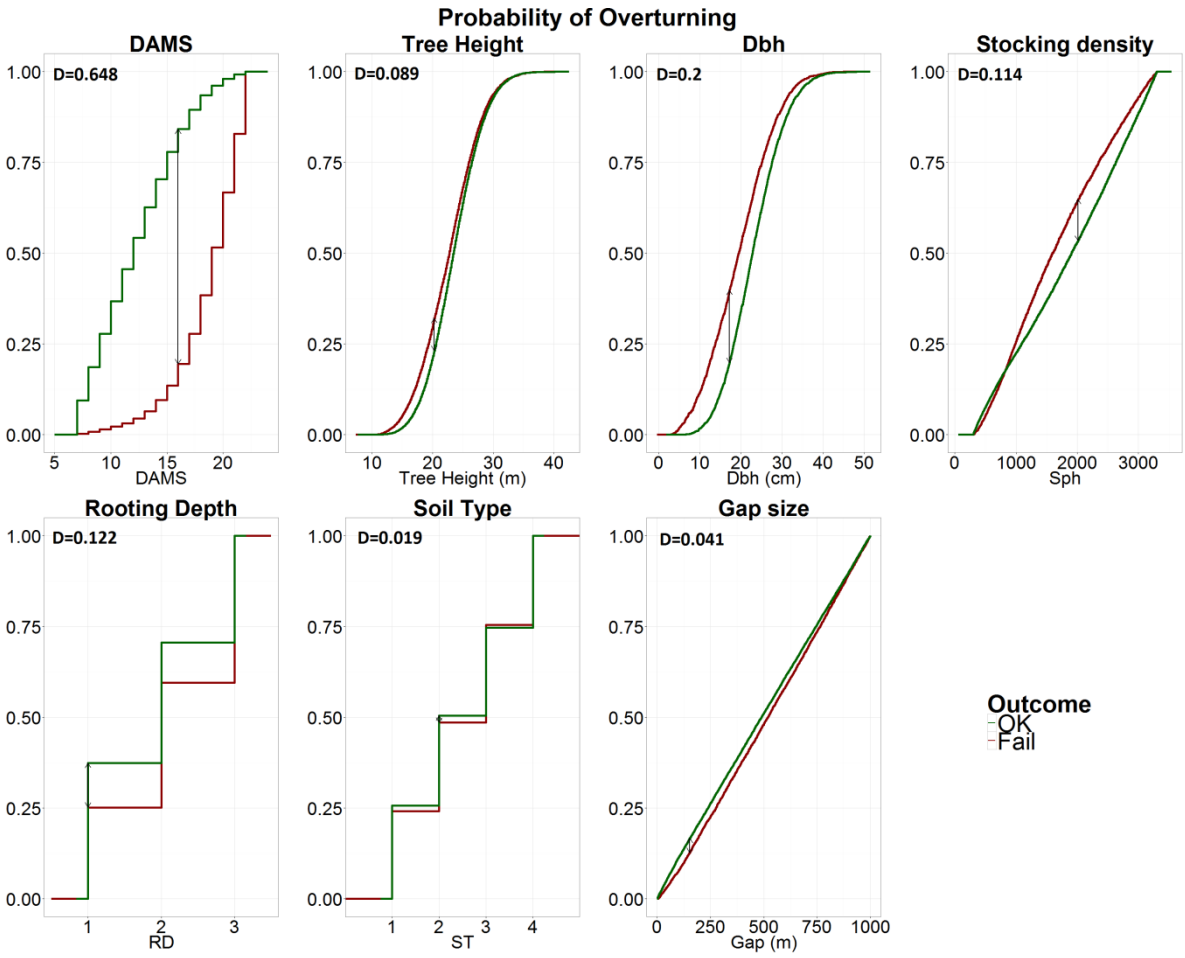


Figure 5.19 - Cumulative density function plots of the probability of overturning for *E. globulus*. DAMS: Detailed Aspect Methods of Scoring, a measure of the windiness of the site. Dbh: diameter at breast height; Sph: stems per hectare. The green lines represent model realisation in the behavioural region (probability < 0.1). The red lines represent model realisations in the non-behavioural region (probability > 0.1). The arrows indicate the maximum distance between the cumulative distributions. Large distances indicate that the variable is influential, as described by the values of the D-statistic.

Figures 5.20 and 5.21 show the two-way interactions for *E. globulus* for the probabilities of breakage and overturning, respectively.

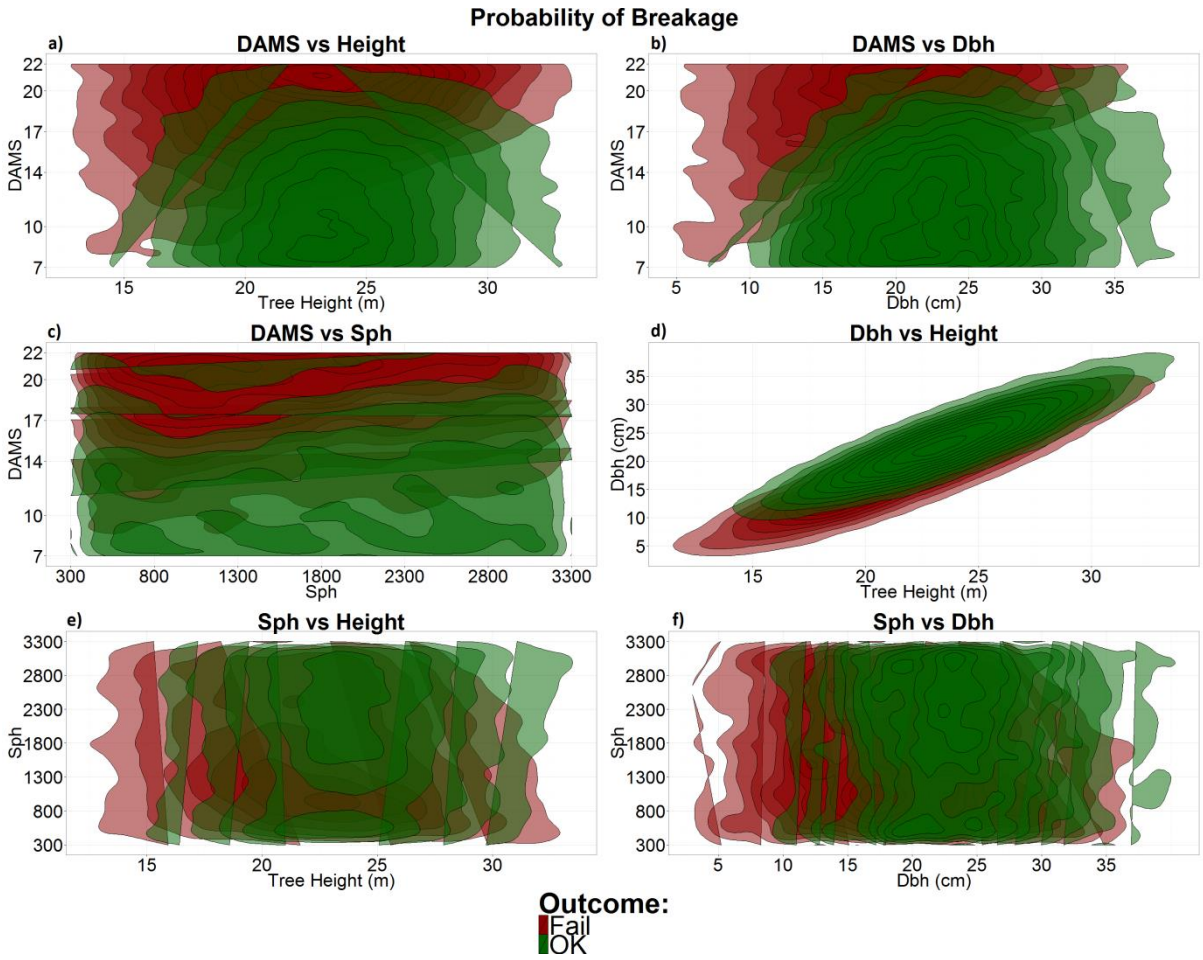


Figure 5.20 - 2D – density plots for probability of breakage for *E. globulus*. DAMS: Detailed Aspect Method of Scoring, a measure of the windiness of a site; Dbh: diameter at breast height; Sph: stems per hectare. The green areas represent the realisations of ForestGALES that correspond to a probability of damage < 0.1. The red areas correspond to probabilities > 0.1. The intensity of the colour corresponds to the density of the outputs: darker areas have higher densities.

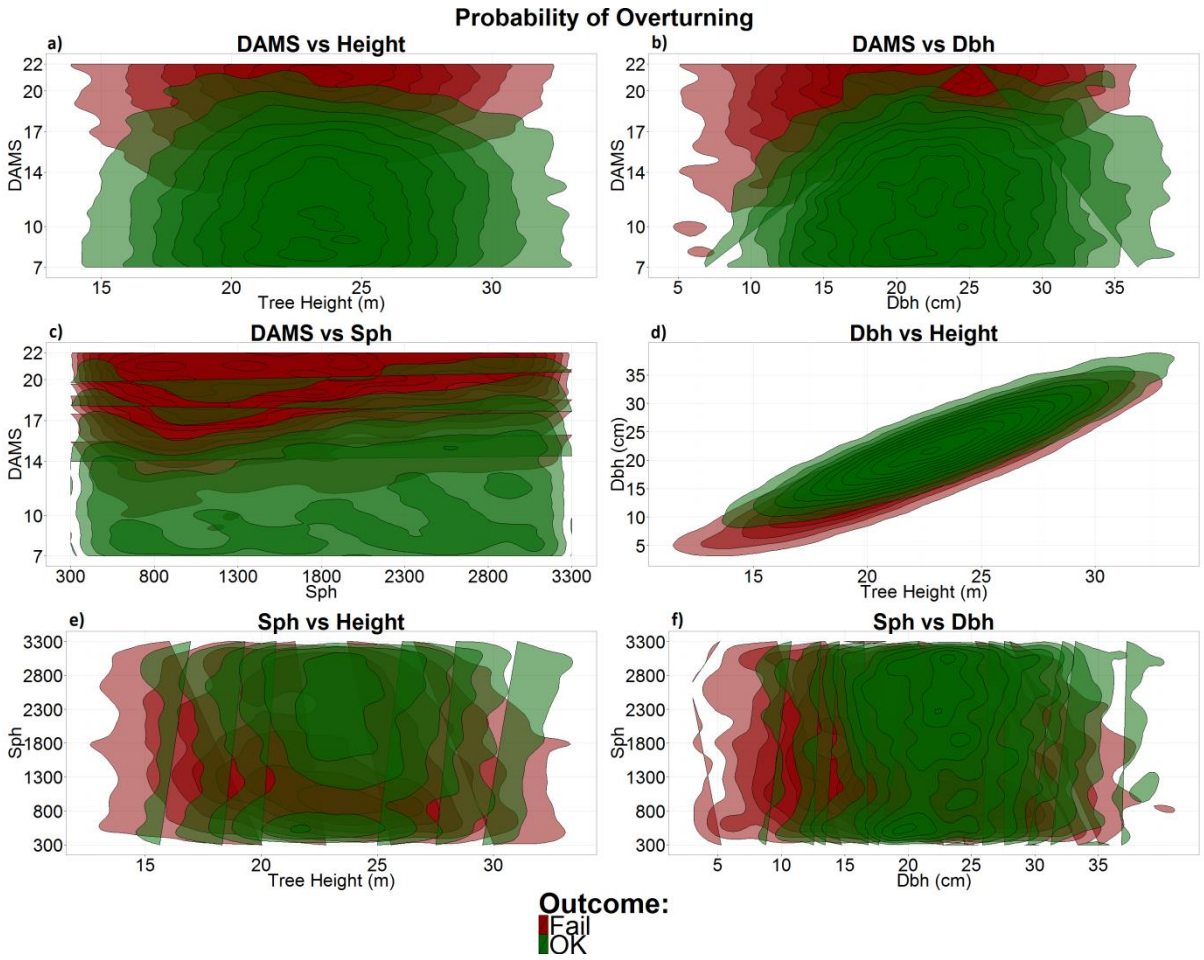


Figure 5.21 - 2D – density plots for probability of overturning for *E. globulus*. DAMS: Detailed Aspect Method of Scoring, a measure of the windiness of a site; Dbh: diameter at breast height; Sph: stems per hectare. The green areas represent the realisations of ForestGALES that correspond to a probability of damage < 0.1. The red areas correspond to probabilities > 0.1. The intensity of the colour corresponds to the density of the outputs: darker areas have higher densities.

For *E. globulus*, the two-way interactions between DAMS, Tree height, Dbh, and Sph, are almost identical for the probabilities of breakage and overturning. For breakage, short trees are at risk of failing for DAMS as low as 8 (Figure 5.20*a*), while for overturning *E. globulus* trees are at low risk regardless of their height, for DAMS lower than 14 (Figure 5.21*a*). Similarly, trees with a small Dbh (< 10cm) are at risk of both breakage and overturning, while as Dbh increases the windiness required to damage a tree increases linearly, with trees of Dbh > 30cm being at risk of damage only for DAMS > 15 (figures 5.20*b* and 5.21*b*). For the interaction between DAMS and Sph, stands of low stocking densities are more prone to damage. However, especially for breakage (Figure 5.20*c*), ForestGALES predicts that low values of DAMS (between 10 and 14) can result in damage to a stand regardless of

its stocking density. The Dbh vs Tree height plots in Figures 5.20*d* and 5.21*d* show that for *E. globulus* ForestGALES cannot discriminate between high and low risk solely on the basis of these two variables, as the density areas overlap almost entirely. However, short trees with small Dbh are predicted to be at higher risk of damage. The last two plots (*e* and *f*) in Figures 5.20 and 5.21 show that short trees, and trees with small Dbh, are at higher risk of damage regardless of the stocking density. Tall trees (>30m) and trees with large Dbh (>30cm) are at lower risk when associated with high stocking densities.

5.4 Discussion

In this study I have performed a variance-based sensitivity analysis (SA) on the forest wind-risk model ForestGALES (Hale et al., 2015). I have used the method of Kucherenko et al. (2012), a generalisation of the Sobol' method (Sobol', 2001) for the case of correlated variables. To provide wide silvicultural and geographical applicability of my results, I have performed my analysis on the performance of ForestGALES for three tree species, representative of three of the most extensively planted and highly productive tree genera in the world: spruces (*P. sitchensis*), pines (*P. pinaster*), and eucalypts (*E. globulus*). I have focussed my sensitivity analysis only on the model input variables that are modifiable by the end-users in order to contextualise my results for practical applications of the model, as well as for the forest wind-risk modelling community. A number of settings are available when performing variance-based SA. These settings make use of different results of the SA, and provide information on different processes within the architecture of a model. In this study I have focussed on three SA settings: Factor Prioritisation (FP), Factor Fixing (FF), and Factor Mapping (FM). ForestGALES provides two pairs of outputs: the critical wind speeds for breakage and overturning ($CWS_{(B,O)}$), and the associated probabilities of damage ($Prob_{(B,O)}$). In this section I first discuss the FP and FF settings that were applied to the $CWS_{(B,O)}$, which I complement with a discussion of the similarities between species in the ranking of the most influential input variables, as identified with the FF setting. I then follow with a discussion of the results of the FM setting which was applied to the $Prob_{(B,O)}$. I conclude this section with an evaluation of the performance of the Sobol' method for correlated variables applied to my study.

5.4.1 Critical wind speeds – Factor Prioritisation setting

The aim of the FP setting is to identify the variables with the highest first-order sensitivity indices (S_i), not taking into account any interactions in the model between the variables. The identification of the variables with the highest S_i values allows optimising the resources required for the acquisition of accurate data for model execution. In fact, high S_i values highlight the variables that, if the uncertainty associated with their measurement or collection is reduced the most, will cause the largest reduction in the uncertainty of the outputs. The two most important variables identified by my SA are Tree height and Sph, regardless of tree species. For *P. sitchensis* differences exist in the ranking of these variables between CWS_B and CWS_O, with Sph being largely more important for the latter than Tree height. Gardiner et al. (1997) have shown that low Sph results in increased wind loading on a tree, promoting overturning over breakage as type of damage. For *P. sitchensis* and particularly for *E. globulus*, Dbh is also influential. For *P. pinaster*, Dbh is completely uninfluential, while variation in Rooting depth contributes marginally to the variation in CWS_O.

For practical applications of ForestGALES, these differences show that managers and owners of small forested stands should tailor their resource allocation to the measurement of different tree and stand variables according to the tree species. Recent advancements in the field of remote sensing can help with fast and cost-effective forest mensuration (McInerney et al., 2011; Rosette et al., 2011). For large applications of the model (i.e. in the Capsis software platform used in France, Dufour-Kowalski et al., 2012), knowledge of species geographical distributions within the area of interest is recommended. However, in the case of mixed-species stands the similarities between the species most influential variables provide some confidence that an average level of measurement accuracy across the variables would ensure that estimates of $CWS_{(B,O)}$ for large-scale investigations of vulnerability are reliable.

The species differences in the FP setting results pose some questions on the inner workings of ForestGALES for different species. For *P. sitchensis*, the influence of Tree height is larger than that of Dbh for CWS_B, while the opposite is true for CWS_O. This is surprising since, as seen in Eq. (2.12) and (2.13) in Chapter 2, Dbh^3 is involved in the calculation of CWS_B, while CWS_O is calculated with stem weight, of which Tree height * Dbh^2 is a good approximation, as shown by Gardiner et al. (1997). However, as shown in Table 5.4 Tree height is involved

in a large number of components of CWS_B, and actually one more than for CWS_O. The FP setting result of Dbh being uninfluential for *P. pinaster* is also surprising. I ascribe this to the fact that the variance of my sample data for Dbh was the smallest of the three species (see Table 5.3). Conversely, the variance of Dbh was largest for *E. globulus*, and its S_i for both CWS is the largest for this species. With regards to *E. globulus*, it is interesting to note that my SA identified some contribution of Gap size to the variance of $CWS_{(B,O)}$, while for the other two species this variable was completely uninfluential. I ascribe this to the fact that in my *E. globulus* sample there is no variation of Rooting depth and Soil type, which therefore cannot outweigh the influence of Gap size, as it is likely to be the case for the other two species. While it is true that Rooting depth's S_i for *E. globulus* is quite high (0.10, Figure 5.8), its S^T_i is zero. Given that there is no variation in Rooting depth and Soil type for *E. globulus*, the non-zero S_i value of Rooting depth is necessarily a mistake in the numerical estimation of the sensitivity indices. Rooting depth is more influential for *P. pinaster* than for *P. sitchensis* (S_i values of 0.13 and 0.01 for CWS_O, Figures 5.6 and 5.2). The likely reason for this is the larger variation in the C_{reg} values for *P. pinaster* than for *P. sitchensis* (Table 5.1). While *P. pinaster*'s C_{reg} values for three soil types (Gleys, Mineral peats, and Deep peats) are actually taken from tree-pulling on *P. sylvestris* (in Nicoll et al., 2006), the largest variation can be seen in the *P. pinaster* bespoke tree-pulling experiments (Cucchi et al., 2004).

5.4.2 Critical wind speeds – Factor Fixing setting

The FF setting is based on the total sensitivity indices (S^T_i) and provides information on the interactions within the model between variables, and on which variables can be confidently fixed at any value within their range without significantly affecting the predictive potential of the model. I first discuss the interactions in ForestGALES, before discussing the issue with fixing variables.

A large difference between a variable's S_i and S^T_i indicate that the variable is involved in a large number of interactions. As expected from Eq. (2.12) and (2.13) and Table 5.2, the largest interactions are expected to be found between Tree height and Dbh, with Sph contributing in a much smaller measure. In fact, my result show that the other variables are not involved in significant interactions, as their S^T_i are basically zero. The largest interactions between Tree height and Dbh are found for *P. pinaster*, with Sph marginally

involved (Figure 5.6). Based on the Sobol' indices in Figure 5.2, for *P. sitchensis* the interactions between Tree height and Dbh are of similar magnitude to those of *P. pinaster*, while Sph is not involved in interactions, with CWS_B showing larger interactions than CWS_O. For *E. globulus*, the interactions between Tree height and Dbh are much smaller than for the other species, while those with Sph are of similar magnitude to *P. pinaster*. To understand the smaller interactions for *E. globulus*, I need to discuss the species-specific calculations in ForestGALES. The main differences are found in the calculations of tree characteristics. Firstly, ForestGALES converts the Tree height variable in the mean height of the stand. When sufficient data from tree-pulling experiments is available (e.g. for *P. sitchensis* and *P. pinaster*) this inevitably results in lower values than those that are input to the model. For species such as *E. globulus*, for which data is limited (see Chapter 3), the conversion is 1:1. That is, the Tree height input data is not modified. For my study, this increases the difference in the heights of my simulated trees between *E. globulus* and the other two species, which are described with lower Tree heights to begin with (see Table 5.3). Tree height is widely accepted as the most important tree characteristic associated with wind damage (e.g. Albrecht et al., 2012; Mayer et al., 2005; Valinger and Fridman, 2011), and my SA shows that ForestGALES does a good job at incorporating it in its predictions of CWS. While there are species-specific differences with regards to the ranking of the most influential variables (Tree height, Dbh, and Sph), these are the same across the three species scrutinised in this study. This finding suggests that the dynamics of wind damage to forests are well described by ForestGALES. Table 5.3 shows that *E. globulus* trees are much more slender than the other species. The role of taper in the vulnerability of a tree to wind damage is well documented (e.g. Cucchi and Bert, 2003; Peltola and Kellomaki, 1993; Quine et al., 1995), with low taper (more slender trees) associated with higher risk. The smaller range of $CWS_{(B,O)}$ calculated for *E. globulus* than for the other species (Figures 5.3 and 5.4) suggests that ForestGALES simulates well the effect of low taper on the vulnerability of trees to wind damage. The influence of tree form on the smaller differences for *E. globulus* in the interaction between Tree height and Dbh found in my study needs to be discussed in conjunction with the calculated $CWS_{(B,O)}$. With variance-based SA methods, the variance of the output is equally important as the variance in the inputs, as shown in Eq. (2.28) and (2.29), in Chapter 2. As shown in the scatterplots in Figures 5.3 and 5.4, the variation in the CWS is larger for *P. sitchensis*, followed by *P. pinaster* and lastly by *E. globulus*, which shows the least variation. Therefore, while the sensitivity indices (and thus

the conditional variances) of the uninfluential variables are of equal magnitude across the three species, the total variance is smaller for *E. globulus*. Total indices calculated with Eq. (2.29) are therefore forcefully smaller for *E. globulus* than for the other species, with the likely result that the magnitude of variables interactions *appears* to be less than for *P. sitchensis* and *P. pinaster*. In addition to this, while the variance of Tree height and Dbh is larger for *E. globulus* than for the other species (Table 5.3), the very high correlation between the two variables for this species (0.91, Table 5.4) has the effect that the relative variance of the two variables (i.e. the bivariate conditional variance) is greatly reduced. I expect this to have an effect on *E. globulus* S^T_i.

Besides the estimation of interactions between variables, the most significant outcome of applying the FF setting is to identify the variables that contribute negligibly to the variance of the output. This has practical advantages, in that when data collection is costly or impractical, resources can be displaced from sampling variables with low S^T_i to those that show a large influence on the output. In the case of ForestGALES, my results calculated negligible S^T_i for Rooting depth, Soil type, and Gap size. The first two are related in ForestGALES as they are used to retrieve the C_{reg} values used in the calculation of CWS_O (Eq. 2.13), and as such are discussed together. My results suggest than accurate knowledge of Rooting depth and Soil type is not necessary, and that only minor approximation errors would follow from fixing these variables to any value within their ranges. These findings suggest that, when Rooting depth and Soil type are not known and would be expensive/impractical to investigate (as for owners and managers of small forested stands), or when they are very heterogeneous (as in the case of large-scale studies of wind damage), these variables can be quite confidently ignored. In fact, the approximation errors shown in Table 5.5 for fixing Rooting depth or Soil type are never larger than 6%. For *P. sitchensis* and *P. pinaster*, when I fixed these variables to the values within their ranges, I did notice some small differences with the "Free" simulations where all the variables were allowed to vary at the same time. As shown in Chapter 3, there is no variation in the C_{reg} values for *E. globulus*, which is therefore not discussed here. I ascribe the relatively high S_i value of Rooting depth for *E. globulus* (0.10) to a numerical imprecision in the calculations. Indeed, the same value is found for CWS_B, and the associated S^T_i were zero. For *P. sitchensis*, fixing Rooting depth to deep rooting resulted in an overestimation of CWS_O, showing more resistance to overturning (Figure 5.5). This reflects the average values of C_{reg} for Rooting depth shown in Table 5.1: the average C_{reg} value of deep Rooting depth is

markedly larger (176.2 N m kg^{-1}) than those for shallow (151.1 N m kg^{-1}) and medium (154.5 N m kg^{-1}) rooting. Similarly, overestimation of CWS_O was found when I fixed Soil type to "Freely draining" (ST1) and "Deep peats" (ST4). The average C_{reg} values for these soil types are the largest for *P. sitchensis* (ST1: 162.5 N m kg^{-1}; ST4: 178.8 N m kg^{-1}). Conversely, fixing Soil type to "Gleys" (ST2, C_{reg} = 143.9 N m kg^{-1}) and "Mineral peats" (ST3, C_{reg} = 157.2 N m kg^{-1}) resulted in an underestimation of CWS_O, apart from when Rooting depth was fixed to deep. For *P. pinaster*, fixing Rooting depth to medium resulted in overestimating CWS_O (Figure 5.7). This is consistent with the C_{reg} values in Table 5.1: not only medium Rooting depth has the largest average C_{reg} value (162.6 N m kg^{-1}) for rooting depths, but it also has the three largest C_{reg} values for *P. pinaster*. With regards to Soil types, an overestimation of CWS_O was obtained when it was fixed to ST4, the soil type with the largest average C_{reg} value (163.7 N m kg^{-1}) across all soil types. Conversely, fixing soil type to ST2 caused an underestimation of CWS_O, due to the fact that this soil type has the lowest Soil type C_{reg} value (131.8 N m kg^{-1}), and two of the lowest C_{reg} values (124.2 and 126.7 N m kg^{-1}).

With regards to the influence of Gap size on $CWS_{(B,O)}$, the Sobol' indices in Figures 5.2, 5.6, and 5.8, suggest that while for *P. sitchensis* and *P. pinaster* Gap size has no influence, it does have an effect on *E. globulus*. However, the scatterplots in Figures 5.3 and 5.4 show that fixing Gap size had an effect on the calculations of the critical wind speeds. This is especially evident for Gap size = 0m, which resulted in large overestimations, especially for *E. globulus*. Fixing Gap size to the other values 1000m and 10 times Tree height resulted in underestimation of $CWS_{(B,O)}$, especially for wind speeds over 25 m s^{-1}, but never for very high $CWS_{(B,O)}$. The effect is more evident for *E. globulus*. Gap sized fixed at 2 times Tree height caused minor overestimation of $CWS_{(B,O)}$ for *P. sitchensis* and *P. pinaster*, also for low wind speeds. For *E. globulus*, the effect is complex, with over and underestimation of the CWS. This is particularly marked for overturning, where very low CWS are affected by the change. Fixing Gap size at 0m means that the stand is part of a continuous forest. As shown by Gardiner et al. (1997), this has the effect of modifying the wind profile, resulting in less loading on the trees (i.e. higher CWS are required to damage a tree within a forest continuum). My results confirm this, showing that ForestGALES is able to simulate the effect of Gap size even in the case of green edges. As shown in Figures 5.3 and 5.4, the effect of fixing Gap size to 0m is evident also at very high CWS, while fixing it to the other values only results in underestimation for medium to moderately high CWS. As the results of the Savage scores indicate (Table 5.6), Tree height, Dbh, and Sph are the most influential

variables in driving the CWS, regardless of tree species. Therefore, high CWS must be associated with short trees, large Dbh, and mid-to-high values of Sph (the latter is shown in the discussion of the probabilities of damage). This is confirmed with data shown in Appendix C: when I isolated the simulated trees associated with extreme CWS (over 75 m s^{-1} for *P. sitchensis*; over 50 m s^{-1} for *P. pinaster*; over 35 m s^{-1} for *E. globulus*), I noticed that these trees were mostly short and their Dbh was large (trees had a large taper), and stocking densities were medium to high. Therefore, for Gap size to be able to have such a large effect when fixed at 0m, it must be more important than estimated with the indices of Sobol'. The Sobol' indices were however able to identify Gap size as more important for *E. globulus* than for the other two species, which is confirmed by my investigation of tree characteristics for extreme CWS shown in Appendix C. In fact, there is much more variation in Tree height, Dbh, and Sph for *E. globulus* trees than for the other species. That is, these trees are taller, their Dbh is not necessarily large, and stocking densities are as low as ~300 sph. Considering that my simulated *E. globulus* trees are much more slender than those of the other two species, and are therefore at higher risk of wind damage, the larger effect of fixing Gap size to 0m is to be expected. The GSA performed with the method of Kucherenko et al. (2012) described in Chapter 3 shows that, when Gap was allowed to vary within the same range as in this Chapter, its influence on the CWS was significant, and the interactions between Tree height, Dbh, Sph, and Gap size were very large. In Chapter 3 the version of ForestGALES treats upwind gaps as brown edges, i.e. gaps recently formed. This suggests that variation of Gap size for newly created gaps has a larger influence on the dynamics of ForestGALES than when the gaps are of the green edge type.

The FF setting can also highlight inadequacies in the modelling of processes that include variables that are found to be important in the natural world. In my study, this is likely to be the case of the influence of Rooting depth and Soil type on overturning. A number of surveys of wind damaged stands have provided information on the factors associated with wind damage to forests. These studies suggest that variation in soil type and rooting depth are important drivers of wind damage (e.g. Hanewinkel et al., 2008; Mayer et al., 2005; Nilsson et al., 2004; Schindler et al., 2009). The authors report that shallow rooting, waterlogged soils, and acidic soils, increase the risk of wind damage. However, these stand characteristics are often time-consuming, expensive, and difficult to measure both during tree-pulling experiments and in forest inventories.

5.4.3 Probabilities of damage – Factor Mapping setting

The FM setting is a form of Monte Carlo filtering, in that it divides the output space in acceptable and unacceptable regions, and maps the realisations of the model in these regions back to the input space. I have applied this setting to the probabilities of breakage and overturning, and I have chosen the probability threshold to differentiate between the two regions in the output space as 0.1 (10% probability of damage). My result show that DAMS, the variable that describes the intensity of the wind, is the most responsible for realisation of $Prob_{(B,O)}$ in the two regions of the output space, regardless of tree species. DAMS values range from 7 to 22, with 20 often regarded as the limit for commercial forestry (Quine, 2000). My SA shows that DAMS values over ~15 are much more likely to result in damage to a stand, regardless of the mode of failure (breakage or overturning) and tree species. This finding suggests that ForestGALES describes well the effect of the wind climate on the probabilities of damage. In fact, it is well known that in the case of extreme wind storm, the effect of silvicultural practices on tree survival is minor (Kohnle et al., 2003), while for sheltered stands the effect of stand and tree characteristics is more prominent (Albrecht et al., 2012). This raises the issue of the availability of accurate wind speed data, which can be obtained only from localised climate stations. While methods to extrapolate spatially the wind speeds exist (e.g. the Wind Atlas Analysis and Application Program (WAsP) used for estimates of wind energy productivity), their extrapolations are not devoid of error, especially in the case of complex terrain or large distances from the data source (Venäläinen et al., 2004). Mayer et al. (2005) have shown that when knowledge of wind speeds during a storm is accurate, wind speeds become important in statistical models used to discriminate between areas with and without wind damage.

The results of the FM setting show some similarities between *P. sitchensis* and *P. pinaster*, and therefore these two species are discussed together. *E. globulus* behaved quite differently, probably due to the tall trees with low taper used in my simulations, and is discussed separately. The results of the Smirnov tests generally agree with the Sobol' S_i calculated for $CWS_{(B,O)}$ for all the species. For *P. pinaster*, this means that Dbh was found to be uninfluential with the Smirnov tests. The role of Dbh in driving the outputs is important for *P. sitchensis*. My results (Figures 5.10 and 5.11) show that the risk of breakage and overturning decreases for trees with a Dbh larger than 10cm. Both conifer species respond

similarly with regards to Sph, as intermediate values (~1500 sph) correspond to lower risk. No threshold could be identified for Tree height. For $Prob_O$, DAMS values lower than 10 did not cause any damage to the simulated stands of the two species (Figures 5.11 and 5.15). The results of my bivariate investigations of the relationship between significant variables with regards to $Prob_{(B,O)}$ show some differences between the two species. For *P. sitchensis*, the two modes of damage show similarities (Figures 5.12 and 5.13). The DAMS vs Tree height density plots show that short trees (Tree height < 10m) are at lower risk of damage regardless of the wind speed, and that no damage was estimated below DAMS ~ 13. I ascribe this behaviour to the form of the *P. sitchensis* trees in my simulations, which are characterised by high taper (Table 5.3). For breakage, *P. pinaster* behaves very similarly, while for overturning higher wind speeds are required for damage (DAMS > 16, Figure 5.17). For both species and both $Prob_{(B,O)}$, the DAMS vs Dbh plots show a diminished importance of wind speed when trees have large Dbh. The role of taper in driving the probabilities of damage is evident from the Dbh vs Tree height density plots. The separation between the clouds of points is quite clear, showing that trees of the same height are at lower risk of damage when their Dbh is large. This finding confirms that ForestGALES simulates effectively the well-known effect of taper on the risk of wind damage (e.g. Peltola and Kellomaki, 1993; Quine et al., 1995). For *P. pinaster*, only trees taller than ~10.5m were considered at risk of damage. The role of Sph is the same for both species and both modes of damage. The DAMS vs Sph plots show that at low stocking densities the probabilities of damage are higher than 10% for DAMS as low as 12, while at high stocking densities damage is predicted only at high DAMS. The relationship between Sph and Tree height in ForestGALES is such that short trees in sparse stands are at lower risk of damage, while trees above 11m are associated with damage regardless of stocking density. Conversely, trees of medium to large Dbh are mostly at risk for low Sph, while low Dbh is associated with damage regardless of the stocking density, but mostly at low Sph. The effect of dense stands is quite constant for the two species, with large stocking densities being associated with lower risk of damage. With regards to Sph, ForestGALES behaves in accordance with the findings of Coutts (1986), who reported less damage in dense *P. sitchensis* stands. Gardiner et al. (1997) showed that low stocking densities result in higher wind loading on the trees, despite the gustiness of the wind decreases with decreasing Sph. The authors showed that the maximum bending moment increases faster than the Gust Factor decreases, as stocking densities decrease.

The FM results for *E. globulus* differ partially from those of the other two species. For both types of damage, the Sph thresholds are lower (~ 1000 sph), as are the associated D-statistic values, suggesting that for *E. globulus* Sph is less important in discriminating between high and low probabilities of damage (Figures 5.18 and 5.19). The density plots (figures 5.20 and 5.21) show that my simulated *E. globulus* trees are at higher risk of damage than the other species, and that DAMS is much more important than Sph, which is in turn much more important than Tree height and Dbh in discriminating between damage and no damage. The DAMS vs Tree height and Dbh plots are very similar, showing that small trees are vulnerable to damage even at low wind speeds (DAMS ~8) while larger trees require DAMS to exceed 14 for the probabilities of damage to exceed 10%. This trend is confirmed by the Tree height vs Dbh plot. I ascribe the similarities between the response of Tree height and Dbh, and the relatively low importance of Sph, to the high taper of my *E. globulus* trees, which probably largely influenced the calculations of $Prob_{(B,O)}$, as for $CWS_{(B,O)}$.

5.4.4 Evaluation of the performance of my GSA

The most important step of variance-based methods of sensitivity analysis is the characterisation of the variables with reliable probability distribution functions. In my study I fitted PDFs to Tree height and Dbh tree-pulling data. Large trees are typically under-represented in these field experiments for safety reasons and technical limitations (Nicoll et al., 2006), even more so for data that was gathered in the past (Fraser and Gardiner, 1967). As a consequence, tall trees are under-represented in the *P. sitchensis* and *P. pinaster* tree-pulling datasets that were used for the PDFs in my study, while short/medium-sized trees with a high taper are common. The high correlation coefficient between Tree height and Dbh (*P. sitchensis*: 0.54; *P. pinaster*: 0.73) resulted in my simulated trees for the two conifer species to be quite short and with a high taper. In addition to this, the taper of my simulated trees was independent of the stocking density, which is not representative of reality. As discussed in the previous paragraphs, these factors have a significant impact on the ForestGALES calculations of the critical wind speeds and their associated probabilities of damage. Consequently, the influence of Sph on the outputs of ForestGALES was probably underestimated in my GSA, as shown by the small differences between total and first-order sensitivity indices for Sph. This is likely to be the case also for *E. globulus*, for a similar but

opposite reason. In fact, my simulated eucalypt trees are fairly tall and slender, with a very high taper. Because of the importance of Tree height, Dbh, and taper in ForestGALES, the outputs are likely to have been mostly driven by Tree height and Dbh, while the role of Sph was probably outweighed. The effect of this can be seem in the smaller range of $CWS_{(B,O)}$ for *E. globulus* in comparison to the other species, as seen in Figures 5.3 and 5.4. Although Tree height and Dbh, and their high correlation (0.91) are representative of the fieldwork data used to calculate the parameters of the corresponding PDFs, the source of my *E. globulus* data has some limitations and might not be representative of all eucalypt stands (see Chapter 3). Nevertheless, my GSA allowed me to highlight the limitations of the parameterisation of ForestGALES for this species. My study shows that the GSA method of Kucherenko et al. (2012) is very sensitive to the correlations between variables in the correlation matrix of the copula. Therefore, it requires an accurate characterisation not only of the PDFs of the inputs, but also of their initial correlation matrix. This is important, to ensure that the generated dataset used for the SA is representative of the original sample's structure.

I described Rooting depth and Soil type with uniform discrete distributions in order to explore the input space more thoroughly, but I did impose a correlation based on *P. sitchensis* data. This might not be representative of *P. pinaster*, and might have marginally influenced my results for this species. Gap size is the variable that is most likely to have been poorly characterised using the range of values in my simulations. As shown in Figures 5.3 and 5.4, fixing Gap size to 0m has a large effect on the calculations of the CWS; at just two tree heights, however, the effect is largely diminished, while the fixing Gap size at values as low as 10 times Tree height has an almost negligible effect. However, the model runs where Gap had values close to 0m were not sufficient to influence the calculations of the Sobol' indices. A Gap of the size of twice the mean Tree heights shown in Table 5.4 belongs to the first quartile of the range of Gap size. Therefore, most of my simulations had values that exceed this average value, and this likely influenced the calculations of the Sobol' indices. I expect that a narrower range of Gap size would have resulted in larger Sobol' indices.

5.5 Conclusion

In this study I have performed a variance-based sensitivity analysis on the forest wind-risk model ForestGALES, for three species (*P. sitchensis*, *P. pinaster*, and *E. globulus*) representative of three of the most extensively planted and highly productive tree genera worldwide: spruces, pines, and eucalypts. My results show that Tree height, Dbh, and stocking density are the variables mostly responsible for the variation in the critical wind speeds for breakage and overturning, and their associated probabilities of damage, regardless of tree species, although minor intraspecific differences exist in the ranking of these variables. Therefore, for practical applications of ForestGALES, users should focus their resources on sampling accurately these three variables to maximally reduce the uncertainty in the predictions of the model. My study shows that Rooting depth and Soil type are only marginally important for the calculations of the critical wind speed of overturning. This finding suggests that these variables can be fixed at any value within their ranges without significantly affecting the output of the model, thus suggesting that ForestGALES can be successfully applied to large-scale studies of wind damage when information on these variables is coarse at best. While there is not a general consensus on the role of these variables on the vulnerability of a stand to wind damage, my study suggests that the empirical component of ForestGALES for the calculation of the resistance to overturning requires further development. The effect of an upwind gap on the critical wind speeds is confirmed also for pre-existing forest edges, suggesting that recommendations made with ForestGALES on the careful management of forest edges to reduce the risk of damage are to be considered seriously, namely avoiding Gap sizes larger than twice the mean height of the stand. The application of the variance-based sensitivity analysis method for correlated variables shows great sensitivity not only to the characterisation of the variables with appropriate probability density functions, but also to the correlation matrix of the variables. Therefore, particular care must be exercised when describing the input data for this method of sensitivity analysis.

Chapter 6 Thesis summary and conclusions

6.1 Introduction

This thesis focussed on the mathematical modelling of the risk of wind damage to commercial plantations using the ForestGALES model. Special emphasis was given on the comparison of the vulnerability to wind damage between commercially important plantation species, and on the assessment of the behaviour, performance, and structure of the model. This chapter therefore discusses the aims achieved and presents a synthesis of the main results, principal limitations, and key conclusions to each chapter. The results of my thesis are aimed at forest owners and managers, and at the forest modelling community. Three objectives were defined in the Introduction:

1. To parameterise and evaluate the performance of ForestGALES for *Eucalyptus globulus* (Labill.). The methods presented are consistent with the current tree-pulling fieldwork techniques, and with best-practice in environmental modelling;
2. To use ForestGALES model simulations to compare the susceptibility to wind damage of *E. globulus* and *Pinus pinaster* (Ait.), to investigate whether *E. globulus* has the potential, from the point of view of wind damage risk, to be a substitute species for *P. pinaster* in geographical areas suitable for these species;
3. To adopt a variance-based method of sensitivity analysis to investigate the sensitivity of the outputs of ForestGALES to its input variables, in order to highlight model sections that need technical or conceptual improvement, and to aid forest practitioners in the small and large scale applications of the model.

These objectives were addressed in the core Chapters 3, 4, and 5. Namely, the first aim pertains to Chapter 3; the second to Chapter 4; the third to Chapters 3 and 5. Therefore, the Chapters are discussed here not in a strictly sequential manner. The last section of this Chapter provides suggestions for future work based on the findings of my thesis.

6.2 Performing and evaluating the parameterisation of ForestGALES for *E. globulus* (Objective 1)

Chapter 3, comprising of a paper published in the journal *Forest Ecology and Management*, provided the first parameterisation of the wind risk model ForestGALES for a non-conifer

species. The choice of *E. globulus* as the first broadleaved species to be added to the list of species already parameterised for ForestGALES was dictated by five considerations: a) the plantation areas of Eucalypt species are extensive, both in the tropics and in temperate areas such as the Iberian peninsula and south-western France; b) the likelihood that the extension and geographical distribution of these planted areas are going to increase in the future is high, in order to meet the increasing demands of fibre, pulp, and biomass worldwide; c) the ability to estimate the risk of wind damage to commercially important plantations species, of which *E. globulus* is a considerable exponent, is fundamental to maximise their productivity; this allows to shift the focus of natural forests management from provisioning services (forest products) to regulating (e.g. carbon sequestration, prevention of soil erosion), supporting (e.g. maintenance of habitat for local species), and cultural (e.g. recreation, mental and physical health) ecosystem services; d) the scarcity of historical wind damage data to Eucalypt species makes it impossible to develop statistical models of wind damage risk to this species; e) process-based environmental models can provide what statistical models cannot – that is, causation and portability to different environmental and climatic conditions. The last consideration is of great interest in view of the projected shifts in the optima of the ecological niches of tree species as a consequence of climate change (Cheaib et al., 2012).

The fieldwork required for the parameterisation was conducted in November 2013 in a semi-natural *E. globulus* forest in the northern Spanish region of Asturias. My results show that trees' resistance to overturning at the site was not significantly influenced by the presence or absence of a tap-root. This is counterintuitive, as one would expect that the presence of a tap root, which in *Eucalyptus* trees can reach considerable size in favourable soils (Stone and Kalisz, 1991), would improve tree anchorage.

The modelling of crown dimensions provided a challenge for the parameterisation of a broadleaved species. This is because the shape of a cone, to which conifer canopies are typically associated with, does not apply to *E. globulus* trees. For these, I opted for an ellipsoid-shaped crown. For broadleaved trees in leaf, it is advisable to measure crown width before the tree-pulling tests, to obtain more accurate results. However, this procedure can be time-consuming when the number of trees is large and manpower is low.

It is outwith the scope of this thesis to discuss in detail the philosophical inadequacy of attempting to validate an environmental model (Oreskes et al., 1994). Some considerations with regards to this issue are briefly discussed in the introduction of Chapter 5. However, even assuming that the validation of environmental models is a feasible and conclusive practice, it was not possible to perform a validation of my parameterisation, due to the scarcity of detailed reports on wind damage to *E. globulus*. In fact, what is typically considered a "proper" validation would have required data on the damaging wind speeds, the dimensions of the damaged and the undamaged trees, and information on stand characteristics such as stocking density, soil type, rooting depth, and size of any upwind gaps. Therefore, I decided to evaluate the behaviour of the parameterisation using model simulations, with regards to the range of tree height and dbh of my experimental trees, different stocking densities, and the presence/absence of an upwind gap. This approach consisted in assessing whether the behaviour of the parameterisation was consistent with the current knowledge of the effect of these variables on the critical wind speeds that can cause damage to a stand. Only one critical wind speed was assessed, chosen as the lowest of those that would result in breakage or overturning.

My results show that *E. globulus* trees respond as expected to variation in tree height, dbh, stocking density, and size of an upwind gap. In fact, the behaviour of my parameterisation is consistent with the findings of several published studies. The risk of wind damage to *E. globulus* trees increases with increasing tree height. The relationship between tree height and vulnerability to wind damage is well known, as reported by Albrecht et al. (2012), Gardiner et al. (2000), Kohnle et al. (2003), and Peltola et al. (2000), amongst others. Chapter 3 shows that, for *E. globulus*, stocking densities are inversely correlated with the critical wind speeds (i.e. they are positively correlated with risk: as stocking densities increase, so does the risk of wind damage). This finding is consistent with the study on balsam fir published by Achim et al. (2005), and with Valinger and Fridman (2011), in their report of the factors affecting the risk of windthrow in Sweden caused by storm Gudrun in 2005. My simulations show that the presence of a freshly established upwind gap increases the risk of wind damage to *E. globulus* stands. This finding agrees with the literature on the effect of upwind gaps on the risk of wind damage to forests. Gardiner et al. (1997) have shown that windward gaps decrease the critical wind speeds, a result of the increased turbulence that is created when gaps are present. Amongst many, Jönsson et al. (2007)

have shown that tree mortality caused by wind is associated with the existence of windward gaps formed recently before the event of a storm.

In light of the results of the evaluation of the behaviour of my parameterisation, suggestions can be made for the management of *E. globulus* plantations to reduce the risk of wind damage. Trees should be planted at medium to high densities to allow for an early thinning when the height of the trees is around 5 to 6m. This would allow a partial initial return on the investments made for the establishment of the stand. Then, complete harvesting of the stand should be carried out before the trees reach a height of 20 to 25m to minimise the time of the rotation when the trees are vulnerable to relatively low wind speeds. Avoidance of newly-created gaps is essential to reduce the risk of wind damage.

6.2.1 Main limitations of fieldwork and evaluation of the behaviour of the parameterisation

- Fieldwork was carried out on just one site. This has reduced the variability in soil types, which can potentially be an important factor for the anchorage of *E. globulus* trees.
- Similarly, the effect of different stocking densities on the wind-firmness of *E. globulus* trees could not be measured, but only simulated.
- The lack of detailed data on wind speed and tree and stand characteristics for events of wind damage to *E. globulus* plantations and/or forest stands means that a "proper" validation could not be performed.

Conclusions A

- I have not been able to confirm the assumed additional resistance to overturning provided to *E. globulus* trees by tap-roots.
- Modelling crowns as ellipsoid is a time-consuming practice. Yet, it describes well the shape of the canopy of *E. globulus* trees.
- The vulnerability to wind damage of *E. globulus* trees increases with increasing tree height and stocking density, and the presence of an upwind gap.
- In light of the evaluation of the parameterisation of ForestGALES for *E. globulus*, management practices to reduce the risk of wind damage to plantations of this species can be suggested. Initial planting at medium/high densities allows for an early thinning to provide an initial return on the establishment costs of the stand, followed by a complete harvest before the trees reach a height of 20 – 25m. Newly created gaps must be avoided.

6.3 Comparing vulnerability to wind damage between *E. globulus* and *P. pinaster* using ForestGALES simulations (Objective 2)

Chapter 4, which has been submitted in paper form to the journal *Forest Ecology and Management*, compares *E. globulus* and *P. pinaster* with regards to the vulnerability to wind damage under environmental and wind climate conditions typical of the Aquitaine region in south-western France. The rationale of my approach originates from the consideration that the wind speeds of storm Klaus (2009) recorded in Aquitaine were very similar to those experienced in the neighbouring Iberian Peninsula. However, the damage to the extensive *P. pinaster* plantations in Aquitaine was catastrophic, with 43.1 Mm^3 of timber losses (Gardiner et al., 2010) which resulted in economic losses of 1.34 to 1.77 billion Euros (Costa et al., 2009), while damage to *E. globulus* forests and plantations in the neighbouring Iberian Peninsula was minor (0.5 to 0.8 Mm^3, from the data reported by Riera (2011) and Trabado (2009)). I used ForestGALES simulations to investigate the effect of rooting depth (2x), growth rates (2 for each species), and presence/absence of a freshly created windward gap, on the critical wind speed of overturning and the associated cumulative probability of damage (CPD), on the two species. The rooting depth for *E. globulus* was modelled with the data on the resistance to overturning of trees with and without a tap-root obtained with tree-pulling tests described in Chapter 3. I chose to focus solely on overturning as the type of tree failure under wind loading because as reported by Cucchi et al. (2005) this was the most common scenario in Aquitaine following storms Martin and Klaus. The two growth rates (slow and fast) simulated for *P. pinaster* were taken from Lemoine and Decourt (1969) and confirmed with Lemoine (1991) as representative of the area. The growth rates of *E. globulus* were based on the report of Moreaux et al. (2013) on the tree heights achievable in *Eucalyptus gundal* plantations in the region. Under similar conditions, *E. gundal* grows a little slower than *E. globulus*, so the slow growth rate used in my simulations might be too conservative.

With regards to the calculated critical wind speeds, my results towards Objective 2 show that young *E. globulus* trees are at lower risk than *P. pinaster* trees of the same age (i.e. their calculated CWS is higher), while as the trees mature the situation is reversed. However, under slow growth rates intraspecific differences are less pronounced. In fact, under suboptimal growth conditions, my results show that both species are relatively safe

from the mean maximum hourly wind speeds recorded for storms Martin (1999) and Klaus (2009). This finding suggests that under this scenario medium to long rotations can be maintained, with higher yields being the result of less frequent harvesting. Conversely, under the fast growth scenario the yields obtainable with *P. pinaster* before the simulated stands reach CWS as low as the wind speeds of the Martin and Klaus storms are about two to three times as large as those with *E. globulus*. The main reason for this is the fact that *E. globulus* fast growth rate is many times faster than that of *P. pinaster*, therefore resulting in *E. globulus* trees having a much lower taper. That is, *E. globulus* trees reach their critical height when their dbh are much smaller than for *P. pinaster* trees. As shown in the Appendix, fast growing *E. globulus* trees reach a height of 22m with a dbh of 15cm at 12 years of age, while fast growing *P. pinaster* trees of the same age are 9m tall, with a dbh of 12 cm.

The presence or absence of a fresh upwind gap significantly influenced my results, with *E. globulus* being more affected. For this species, this results in the height, age, and yields reached in correspondence to the mean maximum hourly wind speeds of the two reference storms being significantly lower with a gap rather than without. However, with regards to *P. pinaster*, an interesting result is that, when not exposed to a fresh gap, *P. pinaster* trees only reach CWS as low as those recorded during storms Martin and Klaus late in their rotation, regardless of the growth rate (height: ~22 – 25m; age: ~40 – 45 years; yield: ~350 – 450 m^3 ha^{-1}). Conversely, in the presence of a gap, their CWS remain almost asymptotical to the reference storm wind speeds for an extended amount of time. This suggests that the explanation advanced by Kamimura et al. (2015), of the main reason for the large losses experienced in Aquitaine being due to the frequent harvesting of neighbouring sites, is supported by my work in Chapter 4. In fact, frequent harvesting results in the almost continuous formation of fresh gaps throughout a continuum of planted and harvested stands. Spatially, this can result in a domino effect, with stands recently exposed to a gap being located at various locations in Aquitaine. Therefore, the high turbulence associated with damaging storms can be regularly "boosted" along the landscape every time the storm reaches a fresh gap. As recently shown by Cristopher Poette of INRA at the first workshop on the mathematical modelling of wind damage held in in October 2015 in Arcachon, France, storm turbulence is not influenced by gap size, but rather by the frequency of the gaps (Poette et al., *in prep.*). Trees that have been recently exposed to a gap have not had

the time to acclimate to the windier conditions thus generated. Not only these trees will be more vulnerable to wind damage, but their demise might also increase the domino effect.

With regards to the cumulative risk that stands of the two species are exposed to through their rotations, the main drivers of risk were found to be the growth rates and the presence of a gap. My results show that, with regards to tree height, *E. globulus* trees are consistently exposed to lower CPD than *P. pinaster* until a height of about 15 – 20m, especially for fast growth rates. In terms of the age of the trees, under the slow growth rate scenario both species behave similarly, reaching CPD=10% at around 20 years. Fast-growing *P. pinaster* trees also reach the CPD threshold at the same age, while fast-growing *E. globulus* trees do so much earlier in the rotation, at around 5 to 7 years. The presence or absence of an upwind gap has a strong effect on the point in the rotation at which *E. globulus* trees reach a critical CPD. Specifically, when a gap is present, *E. globulus* reaches CPD=10% at a height around 15m, while in the absence of a gap this threshold increases to 20m. For *E. globulus*, the effect of an upwind gap is particularly strong for the fast growth rate scenario, likely due to the low taper of these trees, as shown in the Appendix. The behaviour of *P. pinaster* is less affected by the presence of a gap and difference between the two growth rates are smaller than for *E. globulus*. However, the differences between the two growth rates of *P. pinaster* are less pronounced that those of *E. globulus*. Under the fast growth scenario and without a gap, my simulations show that both species reach the same yield (~200 m^3 ha^{-1}) in correspondence to CPD=10%, but *E. globulus* trees require ~10 years to reach this value, while *P. pinaster* require about 20 – 25 years. In light of these considerations, from the point of view of the vulnerability to wind damage, and the associated cumulative risk, silvicultural practices in the Aquitaine region should favour fast-growing *E. globulus* plantations, where possible. In fact, not only fast-growing *E. globulus* stands are exposed to lower cumulative risk than *P. pinaster* for a period of time approximately equivalent to their optimal rotation length adopted in the Iberian Peninsula (12 years, as reported by António et al. (2007) and Riesco-Muñoz (2004)); also, the relatively high yields and short rotation lengths of fast-growing *E. globulus* trees would allow for rapid recovery of any wind-induced losses. This suggestion is corroborated by one of the findings of Chapter 4, that the typical rotation length of *P. pinaster* stands in Aquitaine (~35 years, as reported by Trichet et al. (2009)) falls within an area of CPD larger than 20%. That is, more than one in five chances of damage. Future climatic changes might also affect species selection. Increased surface temperatures might be associated with

reduced winter frost, favouring the shift of optimal growth conditions of sub-tropical species to more northern latitudes. This would favour the selection of *E. globulus*. With regards to water availability, the situation is more complex. In fact, while *Eucalyptus* trees respond very quickly to sudden and large rainfall, showing fast diameter growth (Moreaux et al., 2013), their high water demand might not be satisfied during long periods of drought. The increased frequency of high-intensity storms should however favour short rotation species, such as *E. globulus*.

The results of Chapter 4 show that the contribution of rooting depth to the calculations of CWS and CPD was negligible for *E. globulus* throughout the rotation, and for *P. pinaster* past the juvenile stage. This could be due to the fact that my decision of modelling the presence of a discontinuous hardpan in Aquitaine using shallow and deep rooting depth might have been inadequate. However, the minor effect of rooting depth as a variable of ForestGALES on the model calculations became evident in my sensitivity analysis presented in Chapter 5. This is therefore summarised in the next section.

6.3.1 Main limitations of the comparison of vulnerability and cumulative risk

- Ineffective modelling of hardpan with rooting depth
- Uncertainty over the range of achievable *E. globulus* growth rates in Aquitaine
- From Chapter 3, parameterisation of ForestGALES for *E. globulus* performed on just one site

Conclusions B

- Young *E. globulus* trees are at lower risk of wind damage than young *P.pinaster* trees.
- As the trees get older, the relative vulnerability of the two species is reversed.
- Under suboptimal growth conditions, both species are associated with damaging wind speeds as low as those recorded during the storms Martin (1999) and Klaus (2009) only late in their rotations.
- Conversely, under optimal growth conditions both species become at risk of wind damage at earlier stages of their rotations. This is especially the case of *E. globulus*, due to its exceptionally fast growth rate.
- The silvicultural practices currently in place in Aquitaine expose *P. pinaster* trees to high levels of cumulative risk throughout their rotation.
- In terms of the risk of wind damage, stands of *E. globulus* trees are more susceptible to the presence of a recently created upwind gap.
- In Aquitaine, when fast growth rates can be achieved, short rotations of *E. globulus* trees should be favoured over *P. pinaster* in order to reduce the cumulative risk, while maintaining good yields and allowing for shorter stand recovery time after storm damage.

6.4 Investigating the sensitivity of the outputs of ForestGALES to its input variables using a variance-based sensitivity analysis technique (Objective 3)

The main focus of Chapter 5, and one of the objectives of Chapter 3, is to perform a *global* sensitivity analysis of ForestGALES. Chapter 5 is presently being adapted for submission to the journal *Environmental Modelling and Software*. The main advantages of global methods of sensitivity analysis are the investigation of the entire range of the variables, the evaluation of the interplay between variables, and the applicability to models of unknown linearity. I have applied a variance-based sensitivity analysis to three species for which ForestGALES has been parameterised, to represent three of the most commercially important tree genera worldwide: spruces (*P. sitchensis*), pines (*P. pinaster*), and eucalypts (*E. globulus*). I have decided to investigate the sensitivity of ForestGALES only to the input variables that are user-modifiable, to the benefit of both the community of environmental modellers, and of forest owners and managers. To complement the sensitivity analysis performed in Chapter 3 on the parameterisation of ForestGALES for *E. globulus*, in Chapter

5 I have described an upwind gap as a “green edge”. That is, a gap that has been in place for some time, rather than one that has been recently created (termed “brown edge”).

The global sensitivity analysis has provided insight on the variables that are most important to be known accurately when using ForestGALES in order to maximally reduce the variance of the outputs. Regardless of tree species, these were identified as tree height and stocking density. *P. sitchensis* and *E. globulus* are also very sensitive to variation in dbh, while *P. pinaster* is significantly less sensitive to this. However, dbh is involved in a large number of interactions with the other variables regardless of tree species, suggesting that accurate knowledge of the mean dbh of a stand is important for all species. These findings are relevant for both small-scale applications of ForestGALES, such as for small individual stands, and for large-scale projects (e.g. at regional, national, and European levels). Recent developments in forest mensuration techniques, both on the ground and with remote sensing methods, allow gathering accurate data on these variables relatively fast and inexpensively. The similarities between the three species also provide some confidence that for large-scale projects data collection does not have to be differentiated between species, thus streamlining this resource-intensive and time-demanding process.

The sensitivity analysis performed in Chapters 3 and 5 has shown that large interactions take place between tree height and dbh in the ForestGALES calculations of the critical wind speeds (CWS) for both breakage and overturning. This finding confirms the main architecture of ForestGALES, since these two variables are involved in the calculations of almost all the terms (tree dimensions, canopy roughness, zero-plane displacement, Gust Factor) in the formulas for the calculations of the CWS. The sensitivity analysis result that stocking density is the third variable in terms of number of interactions is also consistent with the main architecture of the model, since this variable contributes just to the calculation of mean spacing and the Gust Factor. It is noteworthy that the estimates of the interactions in which these three variables are involved decrease sensibly when gap is described as a green edge, indicating that the nature of a gap is at least as important to the calculations of the CWS, if not more, as its size.

However, the sensitivity indices calculated for gap as a green edge are probably influenced by the larger range used in Chapter 5. In fact, while in a variance-based sensitivity analysis a larger variance would typically result in an already influential variable being even more influential, as shown by Gardiner et al. (1997) and as discussed in Chapter 5 the effect of

gap does not change significantly for gaps larger than ~4 times tree height. Therefore, most of my simulations used for the sensitivity analysis in Chapter 5 have probably neglected the influence of small upwind gaps. This had a negative effect on the calculation of the sensitivity indices of gap size, which was therefore underestimated. As shown in the scatterplots in Chapter 5, fixing gap size to 0m resulted in significant overestimations of the CWS, fixing it at 2 times tree height had a much smaller effect, and fixing it to larger values resulted in just minor underestimations. These effects were particularly large for *E. globulus*, which is consistent with the findings in Chapter 4 of *E. globulus* being more sensitive to the presence of a gap than *P. pinaster*.

The most surprising result of the sensitivity analysis was that rooting depth and soil type were found to be uninfluential on the calculations of the CWS for overturning. In fact, in ForestGALES the resistance of a tree to uprooting is based on the empirical data acquired with tree-pulling tests. The approximation errors for fixing either of these two variables were smaller than 6%. These findings suggest that, with the current model, surveys of soil types and rooting depth are unnecessary for practical applications of the model. For small-scale applications, this removes the extensive resources required for the exploration of soil types and rooting depths in the area of interest. For large-scale applications, where these two variables are going to be heterogeneously distributed across the landscape, these findings extend the applicability of the model. However, these findings also highlight the inadequacy of the current approach to the modelling of trees resistance to overturning. In fact, numerous statistical studies of the tree and stand characteristics associated with the occurrence of wind damage highlight the importance of soil quality and rooting depth as discriminants of areas with and without wind damage (e.g. Hanewinkel et al., 2008; Mayer et al., 2005; Nilsson et al., 2004; Schindler et al., 2009). These studies show that soil acidity and waterlogging, and shallow rooting depth increase the risk of damage.

The sensitivity analysis in Chapter 5 has shown that the windiness of a site is the main driver of the probability of damage, regardless of tree species and type of damage. A British classification of windiness was used, based on DAMS (Detailed Aspect Method of Scoring) scores, which range from 7 to 22. My results show that exceeding a DAMS score of 15 quickly increases the risk of damage. The three species behave slightly differently with regards to the estimations of the probabilities of damage, with *P. sitchensis* and *P. pinaster* being more similar than *E. globulus*. For *P. sitchensis*, DAMS smaller than 10 result in very

low probabilities of overturning, while for *P. pinaster* this threshold is at DAMS ~16, reflecting the significant differences between the empirical resistance to overturning of these two species. Both species show that at low levels of stocking density high probabilities of damage are obtained also at sites with low windiness, while high stocking densities have very low probabilities of damage until high values of DAMS. This shows that ForestGALES simulates well the findings of Coutts (1986) and Gardiner et al. (1997). Due to the high taper of my simulated *P. sitchensis* and *P. pinaster* trees, the effect of tree height and dbh is difficult to separate from the form of the trees. However, my results show that for both species trees shorter than 10m are at lower risk of damage. Similarly, *P. sitchensis* trees of dbh larger than 10cm have lower probabilities of damage. For *P. pinaster*, dbh was uninfluential for the estimation of the sensitivity of the probabilities of damage to the inputs of ForestGALES. Because of the similar values of the correlation between dbh and tree height for *P. sitchensis* and *P. pinaster* (0.54 and 0.73, respectively), I expect the effect of dbh on the probabilities of damage to be similar between the two species. For *E. globulus*, the importance of DAMS was larger than for the other two species, and the effect of tree height and dbh considerably smaller. In fact, ForestGALES predicted high probabilities of damage for small *E. globulus* trees for DAMS as low as 8, and for large trees for DAMS ~14. As previously discussed, the low taper of my simulated *E. globulus* trees likely influenced the results of the sensitivity analysis in Chapter 5. In fact, the variance-based sensitivity analysis method of Kucherenko et al. (2012) for correlated variables requires knowledge not only of the probability distribution functions (PDF) of the variables under scrutiny, but of their correlation matrix as well. As shown in Chapter 5, for precise evaluation of the sensitivity indices, highly accurate knowledge of the PDF and correlation matrix is required.

6.4.1 Main limitations of the variance-based sensitivity analysis

- Imprecise characterisation of the form of the trees, including the effect of stocking density on tree taper.
- Range of gap size was excessive for the computation of the sensitivity indices.
- The parameterisation of ForestGALES for *E. globulus*, with data restricted on just one site, prevented the investigation of the effect of soil type and rooting density for this species.

- The correlation matrix between the input variables, calculated from *P. sitchensis* data (by far the largest dataset available) might not be representative of the other two species.

Despite these limitations, the sensitivity analysis has shown that ForestGALES describes well the dynamics of wind damage to forested stands, as it simulates well the effects of the most important variables driving the risk of wind damage: tree height, dbh, and stocking density. The effect of low and high taper on the risk of damage is well represented by ForestGALES, as is the effect of gap even in the case of green edges. The perhaps excessive range of gap size used in Chapter 5 has shown that ForestGALES describes well the diminished effect on the wind loading on trees of gaps larger than 10 times tree height. In addition to this, comparing the results of the sensitivity analysis in Chapter 3 with those in Chapter 5 shows that the calculations of the CWS are more heavily affected by gaps with brown edges rather than with green edges, suggesting that ForestGALES is able to account for the effect of newly created gaps. Lastly, Chapter 5 shows that the model is responsive to the predominant influence of the wind speeds to the probabilities of damage: as shown by Kohnle et al. (2003) and Albrecht et al. (2012), there is little scope for silvicultural practices (which can alter tree height, dbh stocking density, and gap size) when storms are exceedingly violent: in this cases, trees will fall despite all human efforts.

Conclusions C

- ForestGALES simulates effectively the dynamics of wind damage to trees regardless of tree species, identifying the tree and stand characteristics that have the largest effect on the vulnerability of a stand to wind damage: tree height, dbh, stocking density, and size of an upwind gap.
- The model differentiates well between the effect of a recently formed gap and a pre-existing one on the critical wind speeds of damage.
- Rooting depth and soil type provide very little contribution to the calculations of the critical wind speed for uprooting. Therefore, these can be neglected in applications of the current version of the model, while future versions require improvements with regards to the modelling of the trees' resistance to overturning. However, when information on these variables is available, they should be retained in the simulations.
- The variance-based method of sensitivity analysis for correlated variables requires accurate estimation of the probability distribution functions of the variables, as well as of their correlations.

6.5 Suggestions for future work

In light of the results of the sensitivity analysis, future efforts on the investigation and modelling of tree anchorage and resistance to overturning should be emphasised, to account for the effect of soil and rooting depth on the vulnerability of wind-induced uprooting. However, these are complex issues, and progress might be slow. In the meantime, additional tree-pulling tests should be carried out for *E. globulus* on soils different than that of my fieldwork site. Similarly, tree-pulling tests of other *Eucalyptus* species of commercial importance, such as *Eucalyptus grandis*, *Eucalyptus urophilla*, and *Eucalyptus urograndis*, should be performed. These species have the potential of substituting *E. globulus* for industrial fibre and biomass production, due to their higher genetic plasticity and high yields, and therefore their use is expected to continue increasing. The comparison between *P. pinaster* and *E. globulus* presented in Chapter 4 of this thesis could be expanded to account for pulp and biomass for bioenergy yields, two applications that are shared between the two species. Using tree biomass for bioenergy is becoming increasingly popular, and the risk of wind damage to the source of such biomass should be estimated. Similarly, the economic relation between wind risk and biomass production should be investigated, to compare tree species that are currently used, or share the potential for this application. Lastly, a more comprehensive sensitivity analysis of ForestGALES should be performed. The model makes large use of constant terms, which are

not absolute and should therefore be accompanied with a measure of their uncertainty. Examples are the values of the Modulus of Elasticity, the Modulus of Rupture, the density of green wood, and a number of terms used in the calculation of wind loading on the trees. The effect of these uncertainties on the model calculations should then be investigated with another sensitivity analysis, which might provide invaluable insight for practical and theoretical developments of the modelling of the risk of wind damage.

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Appendix A

Table A. 1 - Details of equipment used in the tree-pulling experiment of *Eucalyptus globulus* (Labill.) in Asturias, Northern Spain.

Tree-pulling equipment		
Name	*Details*	*Purpose*
Vehicle winch	WinchMax 7550	Pulling the rope attached to the test tree
Polyester webbing round-strops	Safe working load: 10t	Securing the heavy winch frame to anchor trees
Load cell	SM5420, Sensel, France; 5,000 kg-force capacity	Measuring the pulling force
Polypropylene woven rope	Safe working load: 10t	Rope used for pulling the trees with the winch
Inclinometers	Series 900 – 45, Applied Geomechanics Inc., Santa Cruz, California, USA	Measuring the bending of the tree
Data logger	Campbell Scientific CR1000	Recording force and angle data at 1 second intervals
Wood mechanical properties testing equipment		
Name	*Details*	*Purpose*
Thermal test chamber	TAS ECO MT135; Temperature Applied Sciences Ltd, Goring Business Park, West Sussex. http://www.tasltd.co.uk	Keeping the samples used to test for MOE and MOR at constant temperature and relative humidity (21^{o}C and 65%, respectively) to maintain MC~12%
Bench-top bending machine	Tinius Olsen H5K-T, QMat Professional Test Zone software	Destructive testing of flitches for MOE and MOR
Oven	GP 330A, R.E. Pickstone Ltd, Culligan house Gateway Centre, High Wycombe, Buckinghamshire, UK. Now trading as Carbolite: http://www.carbolite.com	Bringing the flitches to constant weight, at a temperature of 103^{o}C, for calculations of the MOE and MOR of green wood

MOE: Modulus of Elasticity; MOR: Modulus of Rupture; MC: Moisture Content.

Appendix B

Tables B.1 and B.2 show the age, tree height, dbh, stocking density, and volumes of the two growth rates used for *Pinus pinaster* (Ait.) and *Eucalyptus globulus* (Labill.), respectively, for the comparisons described in Chapter 4. Tables B.3 and B.4 show the results of the ANCOVA (Analysis of Covariance) tests for the critical wind speeds and cumulative probabilities of damage reported in Chapter 4.

Table B. 1 - Volumes of standing timber and of thinnings for *P. pinaster*'s Yield Classes 2 and 4 (from Lemoine and Decourt, 1969).

Yield Class (2=Fast; 4=Slow)	Trees Age (years)	Volume of standing timber (m^3ha^{-1})	Volume of timber from thinnings (m^3ha^{-1})	Top Height (m)	Dbh (cm)	Sph
2	12	60.8	n/a	9	12.4	1276
	16	112.4	25	12	17.6	817
	20	158.4	33.7	14.8	22.8	517
	24	196.6	42.9	17.3	27.8	385
	28	249.7	41.4	19.6	32.5	298
	34	311.2	59.9	22.4	38.3	245
	40	382.9	34.1	24.6	42.5	217
	46	434.1	21.3	26.2	45.2	199
	54	496.5	17.4	27.4	47	205
	62	514.5	7.2	27.8	47.8	193
4	12	49.1	n/a	2.7	3.6	2268
	16	90.6	14.8	4.9	6.5	2067
	20	127.3	22.1	7.2	9.7	1737
	24	163.3	30.8	9.9	13.9	1112
	28	200.9	35.4	12.4	18.2	772
	34	257.5	46.2	15.7	24.6	453
	40	301	41.3	18.4	30.2	331
	46	338.9	28.7	20.6	34.8	278
	54	375.8	15.6	22.7	39	237
	62	390.1	6.5	23.9	41.1	217

Table B. 2 - Volumes of standing timber for *Eucalyptus globulus*' Site Indices10 10 and 20 (from the GLOBULUS model).

Site Index$_{10}$ (20=Fast; 10=Slow)	Trees Age (years)	Volume of standing timber (m^3ha^{-1})	Top Height (m)	Dbh (cm)	Sph
SI_{10} = 10	6	17.8	5.9	6.5	1155
	7	23.3	7	7.4	1140
	8	31.1	8.1	8.1	1125
	9	41.1	9.1	8.9	1110
	10	50.0	10	9.5	1095
	11	61.1	10.9	10.1	1081
	12	66.6	11.7	10.7	1066
	13	77.0	12.5	11.2	1052
	14	89.5	13.3	11.8	1038
	15	99.9	14	12.2	1025
	16	113.4	14.7	12.7	1011
	17	116.2	15.3	13.1	998
	18	129.9	16	13.6	985
	19	142.6	16.6	14	972
	20	154.3	17.1	14.4	959
	21	157.9	17.7	14.8	946
	22	168.0	18.2	15.1	934
	23	181.8	18.7	15.5	922
	24	192.8	19.2	15.8	909
	25	207.5	19.7	16.2	897
	26	205.9	20.1	16.5	886
	27	218.9	20.6	16.8	874
	28	232.7	21	17.2	862
	29	244.8	21.4	17.5	851
	30	243.3	21.8	17.8	840
	31	255.5	22.2	18.1	829
SI_{10} = 20	3	22.6	7.8	6.7	1202
	4	41.6	10.3	8.3	1186
	5	64.2	12.4	9.6	1170
	6	89.2	14.3	10.7	1155
	7	110.0	16	11.7	1140
	8	137.8	17.5	12.6	1125
	9	165.6	18.8	13.4	1110
	10	192.2	20	14.1	1095
	11	222.2	21.1	14.8	1081
	12	235.2	22.1	15.4	1066
	13	263.3	23.1	16	1052

Appendix C

Figures C.1, C.2, C.3, C.4, C.5, C.6, C.7, C.8, C.9, C.10. C.11, and C.12 show the scatterplots for the results of the sensitivity analysis on Rooting depth and Soil type investigated one at a time, for the three species under scrutiny (*Picea sitchensis* (Bong.) Carr., *Pinus pinaster* (Ait.), and *Eucalyptus globulus* (Labill.)), and both critical wind speeds (breakage and overturning). Table C.1 shows tree height, dbh, and stocking density of the simulated trees associated with extreme critical wind speeds (over 75 m s^{-1} for *P. sitchensis*; over 50 m s^{-1} for *P. pinaster*; over 35 m s^{-1} for *E. globulus*). Tables C.2 and C.3 show the ForestGALES species-specific parameters for *P. sitchensis* and *P. pinaster*.

P. sitchensis:

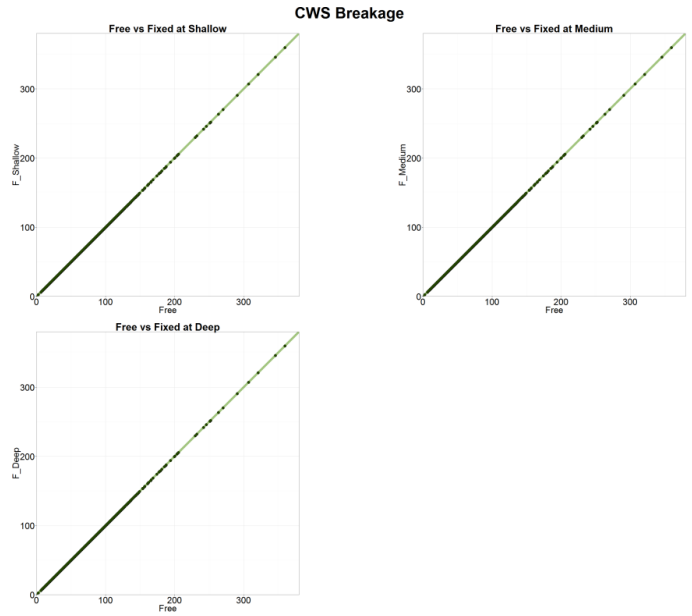

Figure C. 1 - Scatterplots of critical wind speed for breakage for *P. sitchensis*. Rooting depth allowed to vary within its range vs Rooting depth fixed at three different values. Free: all variables allowed to vary within their ranges; F_Shallow: Rooting depth fixed at shallow rooting; F_Medium: Rooting depth fixed at medium rooting; F_Deep: Rooting depth fixed at deep rooting. The green diagonal line represents a 1:1 relationship between the results. Units are m s^{-1}.

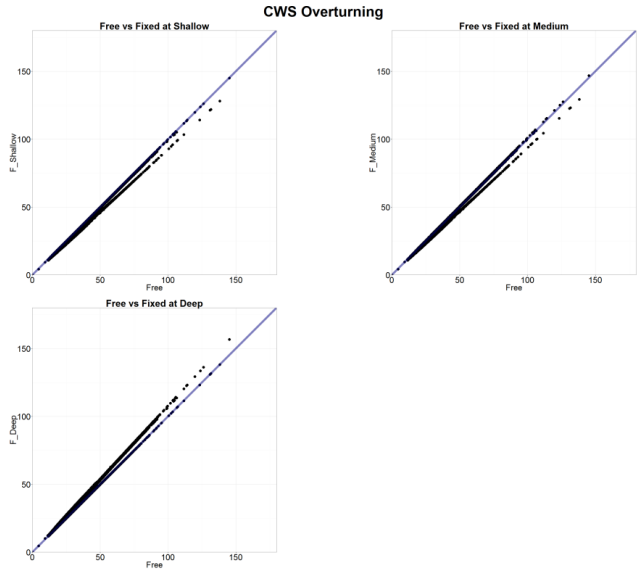

Figure C. 2 - Scatterplots of critical wind speed for overturning for *P. sitchensis*. Rooting depth allowed to vary within its range vs Rooting depth fixed at three different values. Free: all variables allowed to vary within their ranges; F_Shallow: Rooting depth fixed at shallow rooting; F_Medium: Rooting depth fixed at medium rooting; F_Deep: Rooting depth fixed at deep rooting. The blue diagonal line represents a 1:1 relationship between the results. Units are m s^{-1}.

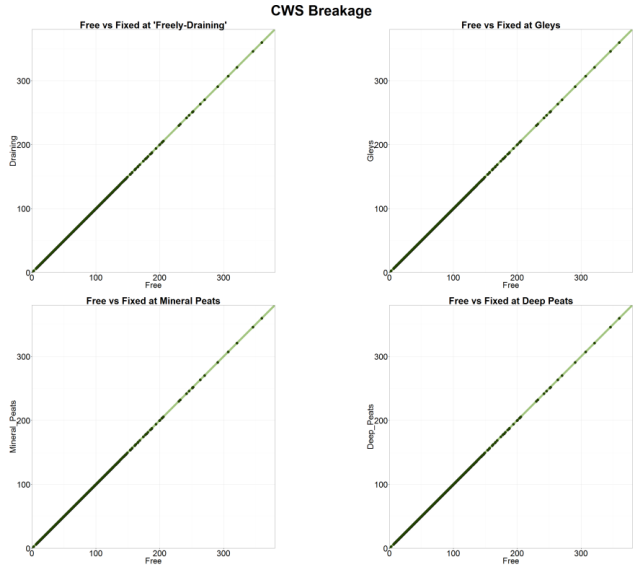

Figure C. 3 - Scatterplots of critical wind speed for breakage for *P. sitchensis*. Soil type allowed to vary within its range vs Soil type fixed at four different values. Free: all variables allowed to vary within their ranges; Draining: Soil type fixed atFreely draining soils; Gleys: Soil type fixed at Gley soils; Mineral_Peats: Soil type fixed at Mineral peats. Deep_Peats: Soil type fixed at Deep peats. The green diagonal line represents a 1:1 relationship between the results. Units are m s^{-1}.

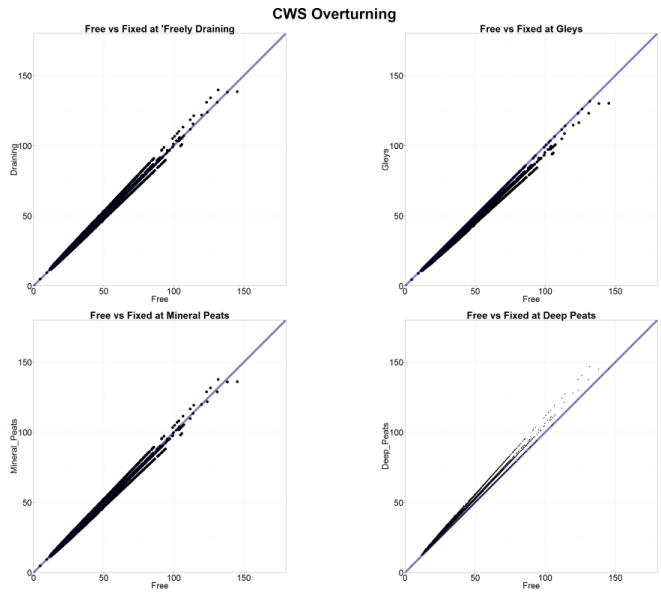

Figure C. 4 - Scatterplots of critical wind speed for overturning for *P. sitchensis*. Soil type allowed to vary within its range vs Soil type fixed at four different values. Free: all variables allowed to vary within their ranges; Draining: Soil type fixed atFreely draining soils; Gleys: Soil type fixed at Gley soils; Mineral_Peats: Soil type fixed at Mineral peats. Deep_Peats: Soil type fixed at Deep peats. The blue diagonal line represents a 1:1 relationship between the results. Units are m s^{-1}.

P. pinaster:

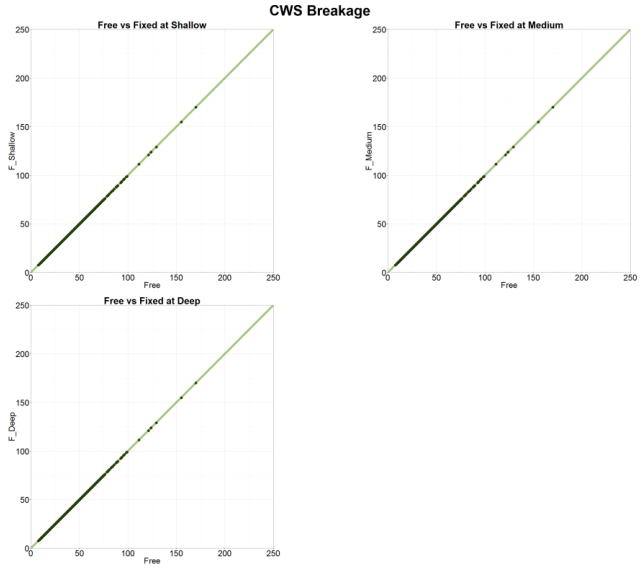

Figure C. 5 - Scatterplots of critical wind speed for breakage for *P. pinaster*. Rooting depth allowed to vary within its range vs Rooting depth fixed at three different values. Free: all variables allowed to vary within their ranges; F_Shallow: Rooting depth fixed at shallow rooting; F_Medium: Rooting depth fixed at medium rooting; F_Deep: Rooting depth fixed at deep rooting. The green diagonal line represents a 1:1 relationship between the results. Units are m s^{-1}.

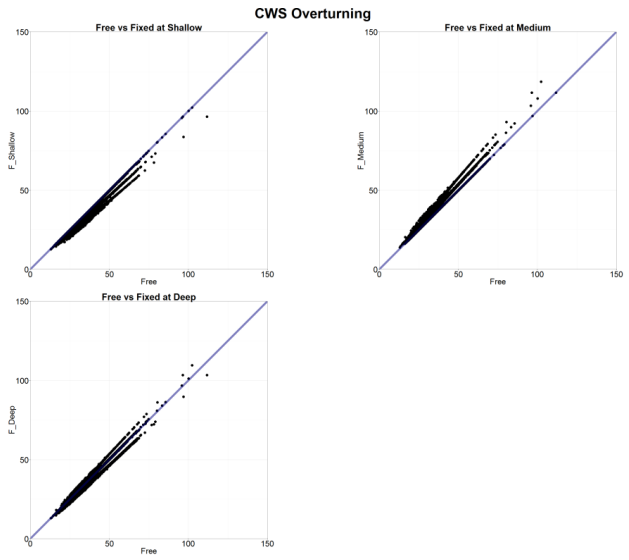

Figure C. 6 - Scatterplots of critical wind speed for overturning for *P. pinaster*. Rooting depth allowed to vary within its range vs Rooting depth fixed at three different values. Free: all variables allowed to vary within their ranges; F_Shallow: Rooting depth fixed at shallow rooting; F_Medium: Rooting depth fixed at medium rooting; F_Deep: Rooting depth fixed at deep rooting. The blue diagonal line represents a 1:1 relationship between the results. Units are m s^{-1}.

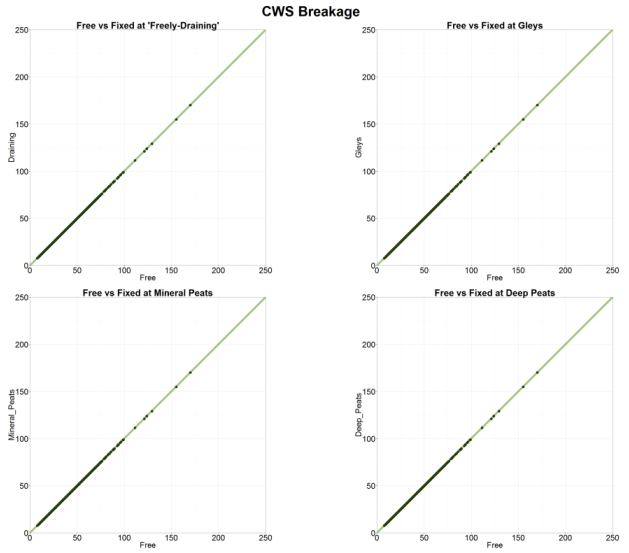

Figure C. 7 - Scatterplots of critical wind speed for breakage for *P. pinaster*. Soil type allowed to vary within its range vs Soil type fixed at four different values. Free: all variables allowed to vary within their ranges; Draining: Soil type fixed atFreely draining soils; Gleys: Soil type fixed at Gley soils; Mineral_Peats: Soil type fixed at Mineral peats. Deep_Peats: Soil type fixed at Deep peats. The green diagonal line represents a 1:1 relationship between the results. Units are m s^{-1}.

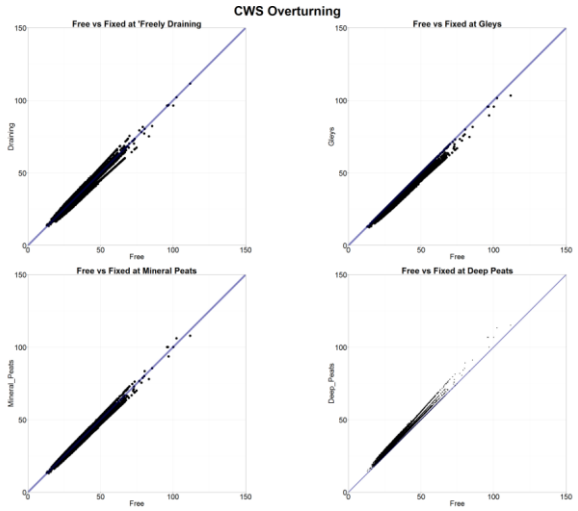

Figure C. 8 - Scatterplots of critical wind speed for overturning for *P. pinaster*. Soil type allowed to vary within its range vs Soil type fixed at four different values. Free: all variables allowed to vary within their ranges; Draining: Soil type fixed atFreely draining soils; Gleys: Soil type fixed at Gley soils; Mineral_Peats: Soil type fixed at Mineral peats. Deep_Peats: Soil type fixed at Deep peats. The blue diagonal line represents a 1:1 relationship between the results. Units are m s^{-1}.

E. globulus:

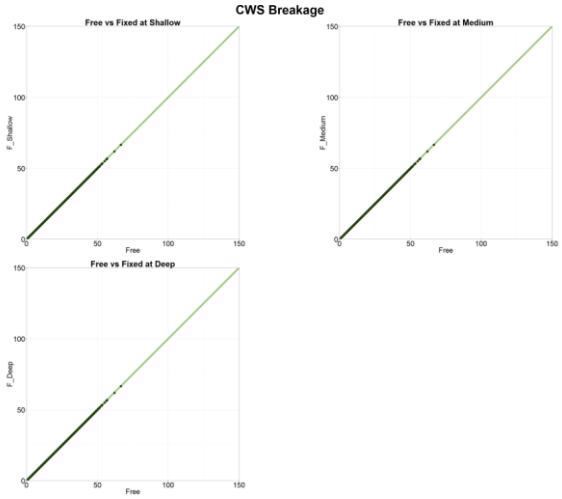

Figure C. 9 - Scatterplots of critical wind speed for breakage for *E. globulus*. . Rooting depth allowed to vary within its range vs Rooting depth fixed at three different values. Free: all variables allowed to vary within their ranges; F_Shallow: Rooting depth fixed at shallow rooting; F_Medium: Rooting depth fixed at medium rooting; F_Deep: Rooting depth fixed at deep rooting. The green diagonal line represents a 1:1 relationship between the results. Units are m s^{-1}.

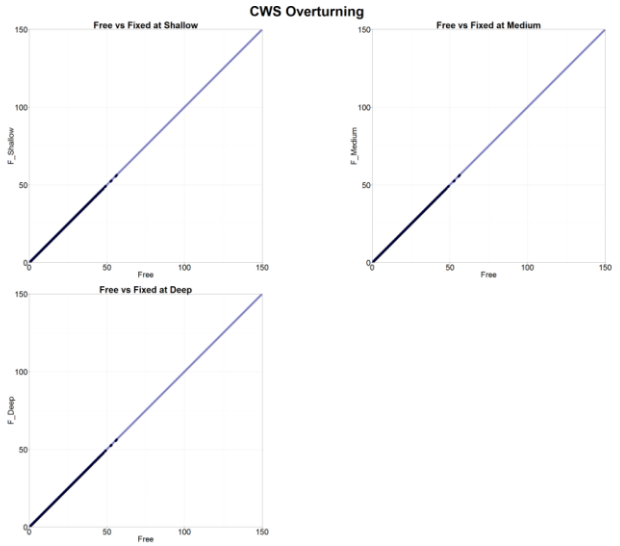

Figure C. 10 - Scatterplots of critical wind speed for overturning for *E. globulus*. Rooting depth allowed to vary within its range vs Rooting depth fixed at three different values. Free: all variables allowed to vary within their ranges; F_Shallow: Rooting depth fixed at shallow rooting; F_Medium: Rooting depth fixed at medium rooting; F_Deep: Rooting depth fixed at deep rooting. The blue diagonal line represents a 1:1 relationship between the results. Units are m s^{-1}.

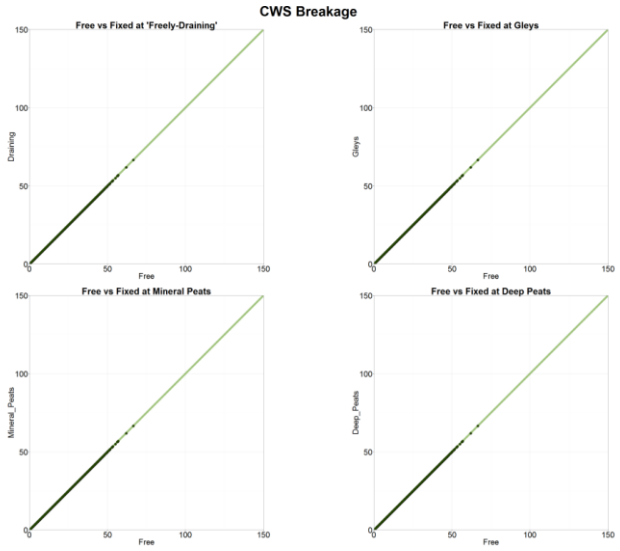

Figure C. 11 - Scatterplots of critical wind speed for breakage for *E. globulus*. Soil type allowed to vary within its range vs Soil type fixed at four different values. Free: all variables allowed to vary within their ranges; Draining: Soil type fixed atFreely draining soils; Gleys: Soil type fixed at Gley soils; Mineral_Peats: Soil type fixed at Mineral peats. Deep_Peats: Soil type fixed at Deep peats. The green diagonal line represents a 1:1 relationship between the results. Units are m s^{-1}.

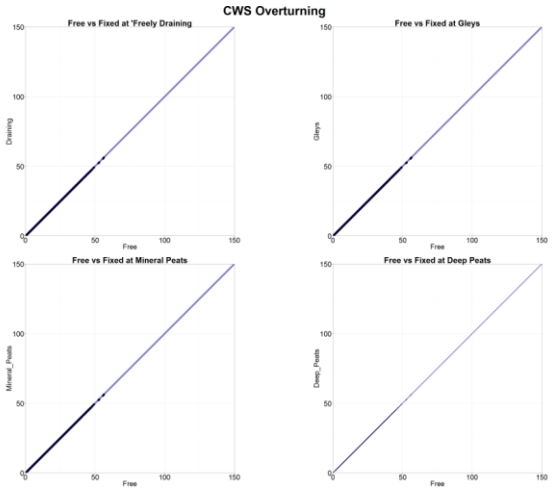

Figure C. 12 - Scatterplots of critical wind speed for overturning for *E. globulus*. Soil type allowed to vary within its range vs Soil type fixed at four different values. Free: all variables allowed to vary within their ranges; Draining: Soil type fixed atFreely draining soils; Gleys: Soil type fixed at Gley soils; Mineral_Peats: Soil type fixed at Mineral peats. Deep_Peats: Soil type fixed at Deep peats. The blue diagonal line represents a 1:1 relationship between the results. Units are m s^{-1}.

Table C. 1 - Tree height, dbh, and stocking density of the simulated trees associated with extreme critical wind speeds (over 75 m s^{-1} for *P. sitchensis*; over 50 m s^{-1} for *P. pinaster*; over 35 m s^{-1} for *E. globulus*).

P. sitchensis	Range	mean	s.d.
Tree height	4.4 - 17.5	10.5	2.3
Dbh	8.4 - 35.3	21.9	4.4
Sph	306 - 3300	2410	662.3
Gap size	0.2 - 997	502.8	291.8

P. pinaster	Range	mean	s.d.
Tree height	4.1 - 14.7	8.9	2.1
Dbh	9 - 26.3	17.9	3.6
Sph	306 - 3300	2143	920.3
Gap size	0.2 - 997	507.7	291.5

E. globulus	Range	mean	s.d.
Tree height	11.6 - 40.1	24	5.3
Dbh	9.5 - 48.1	28.3	7.3
Sph	301 - 3300	2094.6	1031.2
Gap size	0.2 - 999	399.6	318.5

Table C. 2 - ForestGALES *Picea sitchensis* parameters

Parameter	Formula / Value	Comments
Mean Height (m)	1.0467 * Top Height - 2.1452	
Canopy Breadth (m)	0.1346 * *Dbh* *100 + 0.6418	Value of *Dbh* in meters
Stem Density (kg m^{-3})	850	
Canopy Density (branches + leaves: kg m^{-3})	2.50	
Modulus of Rupture (MPa)	34	Calculated experimentally. MOR of green wood
Modulus of Elasticity (MPa)	590	Calculated experimentally. MOE of green wood
Knot Factor	1	
C	2.35	
N	0.51	
Root Bending Term	0	

Table C. 3 - ForestGALES *Pinus pinaster* parameters

Parameter	**Formula / Value**	**Comments**
Mean Height (m)	1.0 * Top Height	
Canopy Breadth (m)	0.15674 * *Dbh* *100	Value of *Dbh* in meters
Stem Density (kg m^{-3})	903.4	
Canopy Density (branches + leaves: kg m^{-3})	2.73	
Modulus of Rupture (MPa)	36	From Lavers (2002). MOR of green wood
Modulus of Elasticity (MPa)	660	From Lavers (2002). MOE of green wood
Knot Factor	0.85	Value borrowed from *Pinus sylvestris*
C	3.07	Value borrowed from *Pinus sylvestris*
N	0.75	Value borrowed from *Pinus sylvestris*
Root Bending Term	0	